Search for supersymmetry in final states with jets and missing transverse momentum with the ATLAS detector

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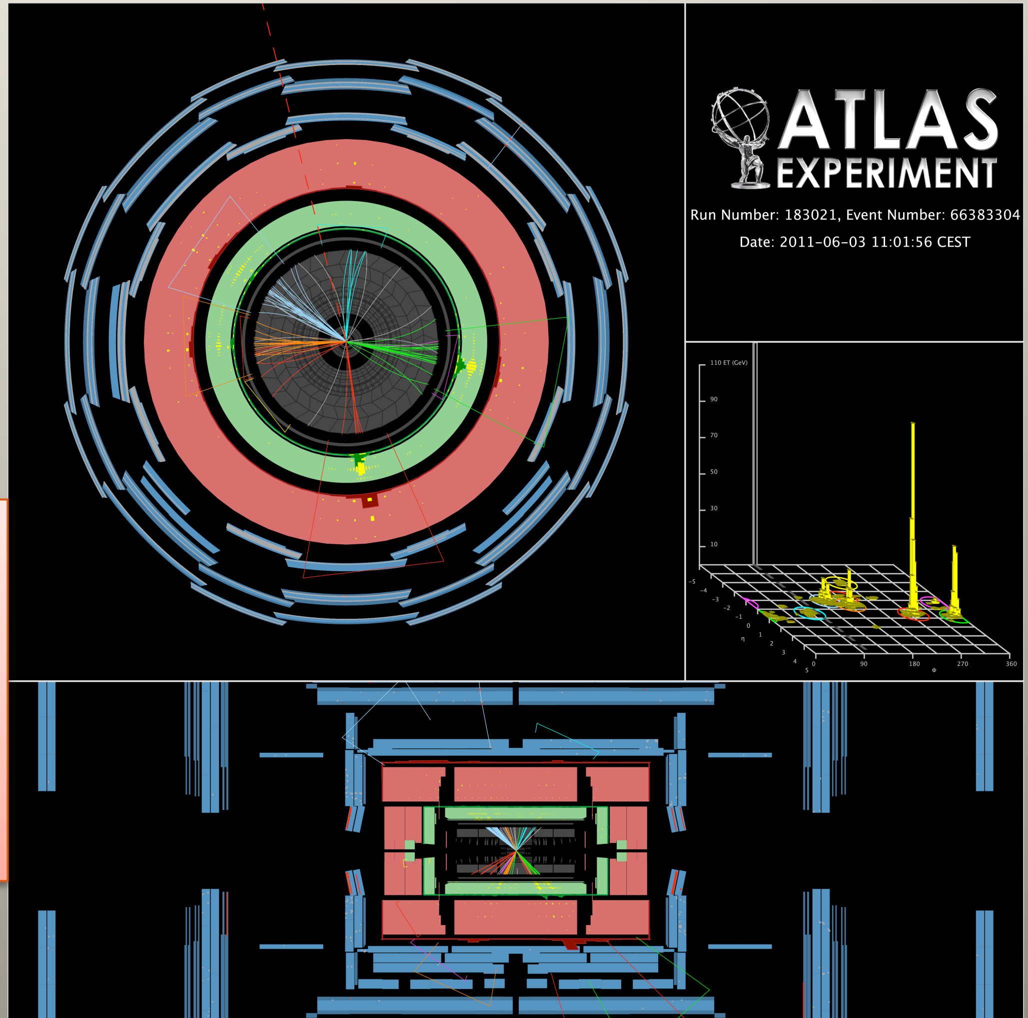
on behalf of the ATLAS collaboration

Supersymmetry 2011, Fermilab

Introduction

- Searches for new **strongly interacting** particles in final states with **jets and missing transverse momentum**
- >1 fb^{-1} analysed at $\sqrt{s}$ = 7 TeV

2-4 jet inclusive search	**6-8 jet inclusive search**
$\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ $\tilde{q} \to q\tilde{\chi}_1^0$ $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	Many-body decays Non-leptonic cascade decays



Object selection

*For veto:
Tighter selections used in leptonic Control Regions (eg $p_T > 25$ GeV)

Jets

Anit-k_T algorithm with R=0.4
$p_T > 20$ GeV, $|\eta| < 2.8$
MC-based calibration with pile-up and vertex corrections

Missing transverse momentum (MET)

Jet-based MET + out-of-cluster contributions
Corrections for loosely-selected electrons and muons ($p_T > 10$ GeV)

Trigger

>95% efficient in signal regions

Electrons and muons*

$p_T > 20$ GeV, $|\eta_e| < 2.47$, $|\eta_\mu| < 2.40$
Muon isolation: $\Sigma\, p_T\ (\Delta R < 0.2) < 1.8$ GeV

Overlap removal

ΔR(e, jet) < 0.2 => remove jet
ΔR(e/μ, jet) < 0.4 => remove lepton

Event veto

Primary vertex has < 5 tracks
Jet quality + other event cleaning
- Including LAr readout problems; veto region of size 1.4×0.2 in $\Delta\eta\times\Delta\phi$

Reconstructed electron or muon
- **covered by independent analyses**

2-4 JET ANALYSIS

Signal Region selection

Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
E_T^{miss}	> 130	> 130	> 130	> 130
Leading jet p_T	> 130	> 130	> 130	> 130
Second jet p_T	> 40	> 40	> 40	> 80
Third jet p_T	–	> 40	> 40	> 80
Fourth jet p_T	–	–	> 40	> 80
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff} [GeV]	> 1000	> 1000	$> 500/1000$	> 1100

Trigger plateau

Jet multiplicity

QCD rejection

Signal definition

$\tilde{q}\tilde{q}$ $\tilde{q}\tilde{g}$ $\tilde{g}\tilde{g}$

$$\int L\,dt = 1.04\ \text{fb}^{-1} \pm 0.04\ \text{fb}^{-1}$$

$$m_{eff} = E_T^{miss} + \sum_{\text{SR jets}} p_T$$

$$m_{eff}^{incl} = E_T^{miss} + \sum_{p_T > 40\ \text{GeV}} p_T^{jet}$$

- **Jet + MET** trigger
- **5 Signal Regions**, targeting different topologies and mass ranges
- **Optimised for discovery** using a simplified SUSY model

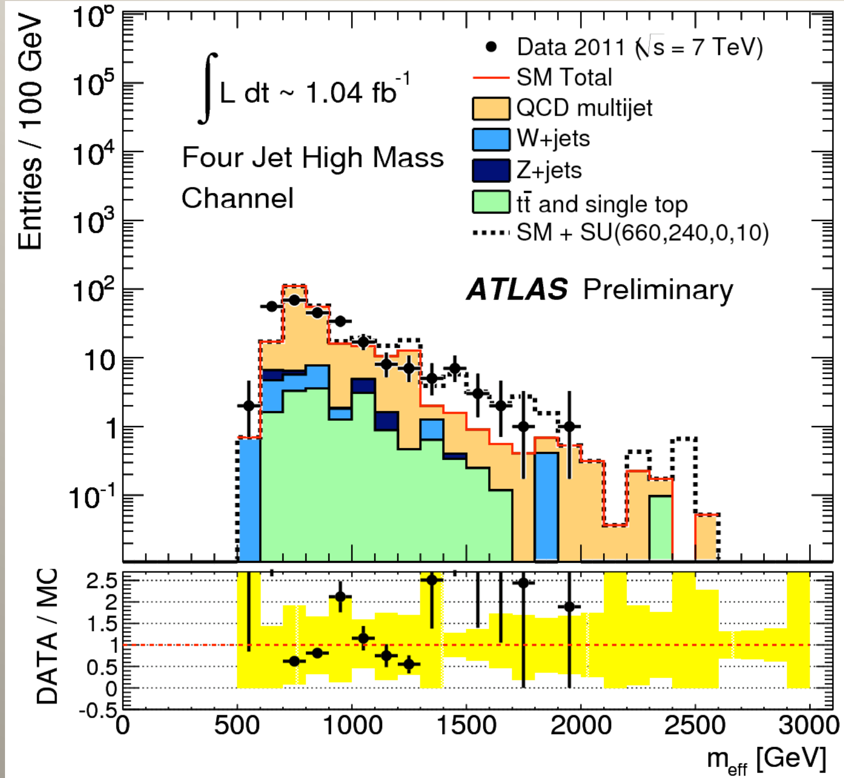
Analysis strategy

- Principal background components:
  - **W/Z+jets** ($Z \rightarrow \nu\nu$ irreducible)
  - **Top**
  - QCD multi-jets
- Estimated using **Control Regions**, five for each Signal Region
  - Input to combined likelihood fit
- **Transfer Factors** relate CR measurement to SR background estimate
  - Ratio reduces some systematic uncertainties

$$N(\mathrm{SR},\mathrm{est},\mathrm{proc}) = N(\mathrm{CR},\mathrm{obs},\mathrm{proc}) * \left[\frac{N(\mathrm{SR},\mathrm{raw},\mathrm{proc})}{N(\mathrm{CR},\mathrm{raw},\mathrm{proc})}\right]$$

- **Profile likelihood fit** accounts for correlated systematic uncertainties and CR contamination

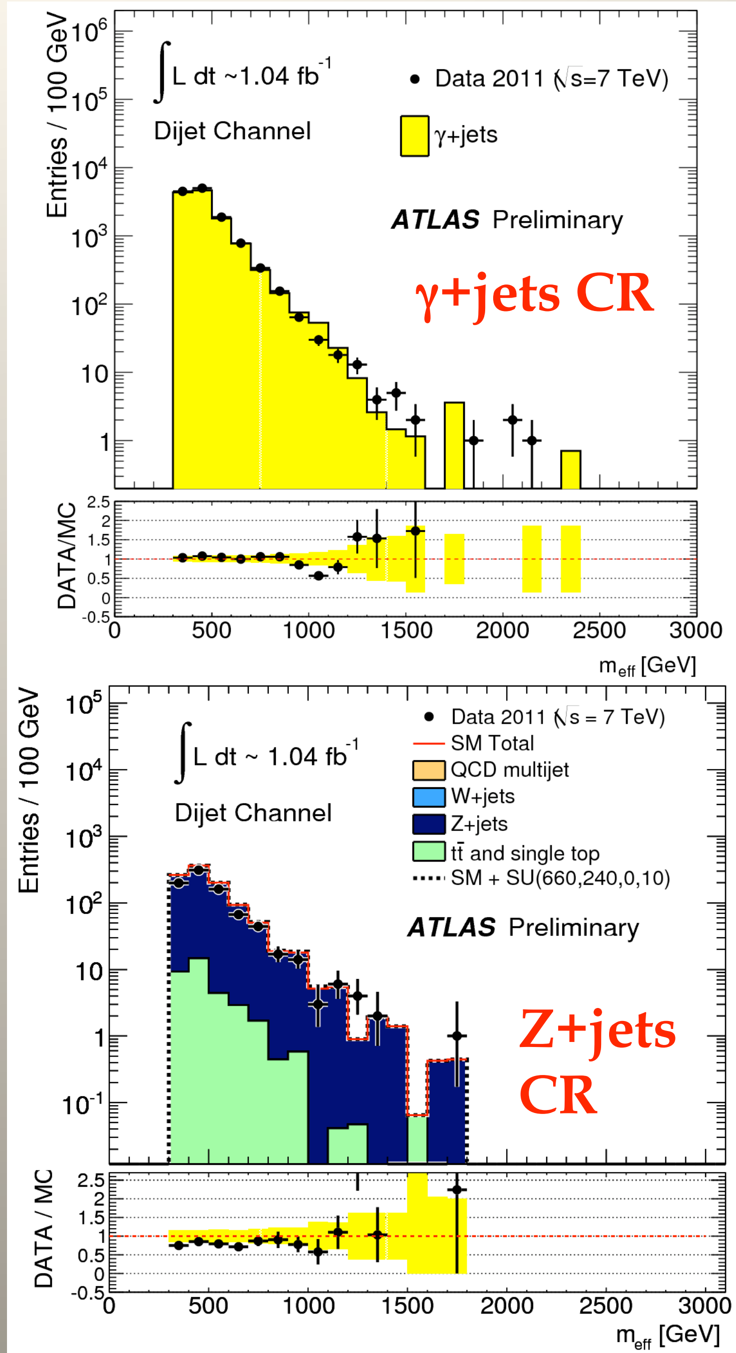
QCD background

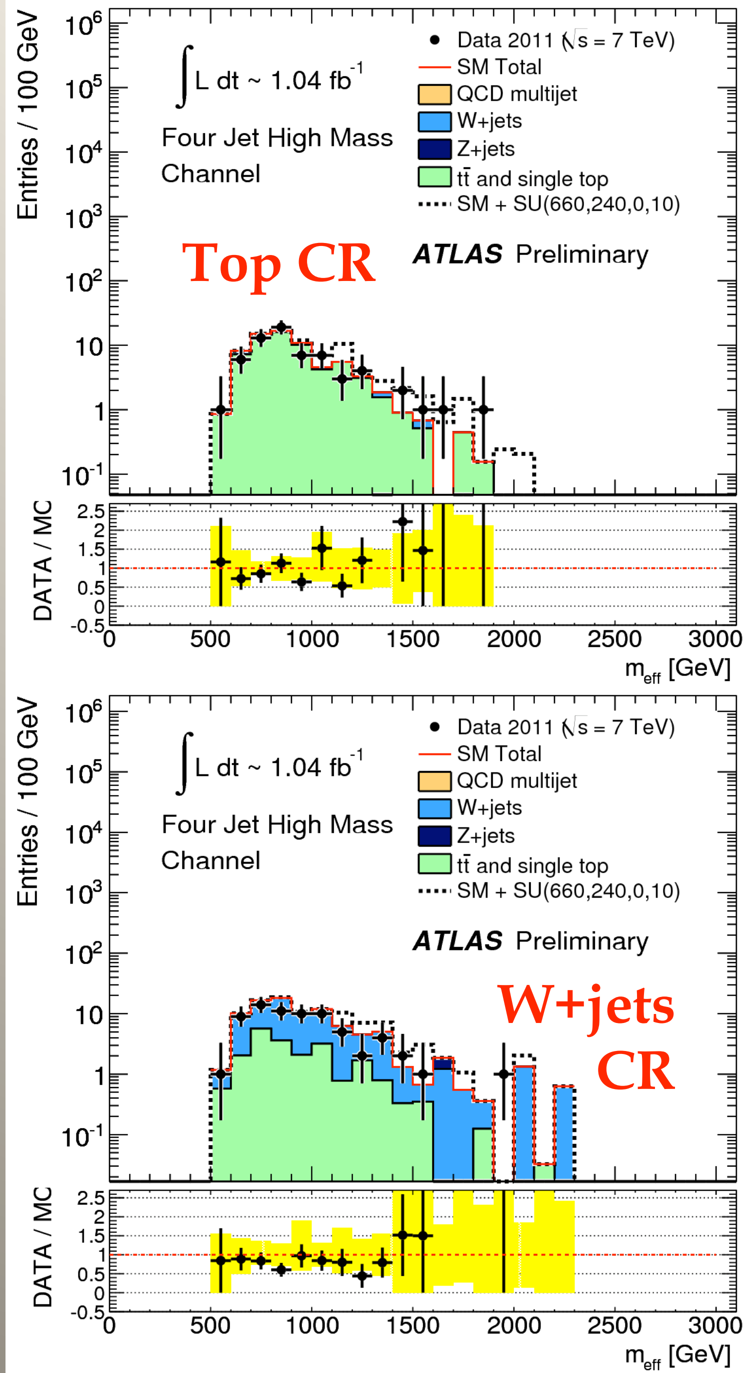


- **Data-driven** background estimation
  - Control region defined by **$\Delta\phi$(jet, MET)$_{min}$ < 0.2**
    - Mis-measured jets
    - Heavy flavour
  - Transfer Factor computed by **smearing jets** in low-MET events
    - Smearing produces high MET events => count SR/CR ratio using $\Delta\phi$
  - Special treatment of region with **LAr readout problems**
- Uncertainties from modelling of jet smearing

Z+jets background

- Two Control Regions
  - **γ+jets**, with photon treated as MET
  - **Z(→ll)+jets**, with Z treated as MET
- Transfer Factors taken from simulation
- Main uncertainties:
  - Theoretical extrapolations
  - Jet energy scale/resolution
  - Other detector systematics
  - MC statistics



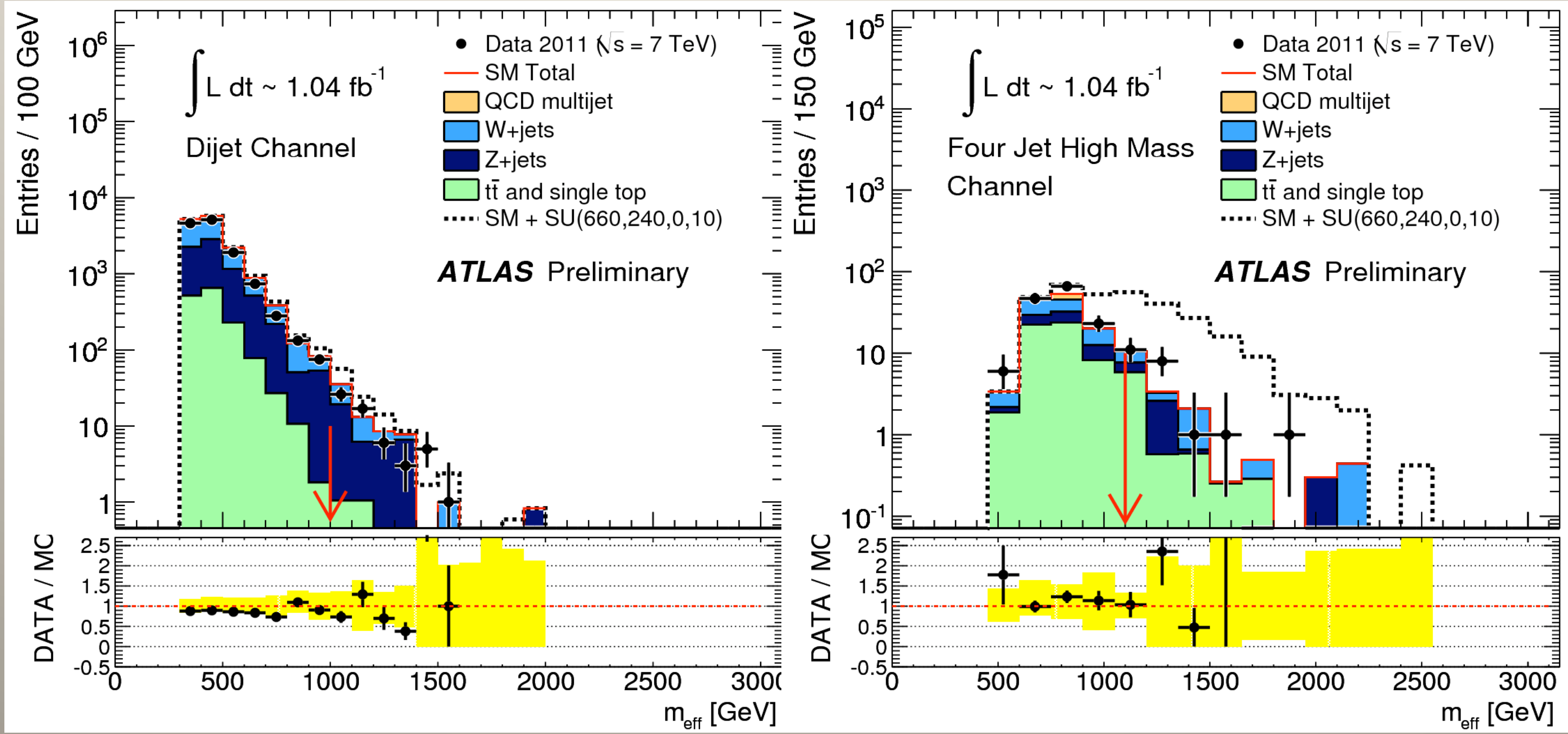


W and top background

- CR events selected with a **lepton + MET** selection
  - **30 < m_T < 100 GeV** *
  - **b-tagged jet** => top CR
  - Otherwise => W CR
  - Lepton treated as jet for other kinematic cuts
- Transfer Factor from simulation
- Main uncertainties:
  - Theoretical extrapolations
  - Jet energy scale/resolution
  - Other detector systematics
  - Pile-up
  - b-tagging uncertainties
  - MC statistics

$$* \; m_T = \sqrt{2 p_T^{\ell} E_T^{\text{miss}} [1 - \cos\Delta\phi(p_T^{\ell}, E_T^{\text{miss}})]}$$

Signal Region observations



- Data and raw MC **agree well**
- Model limits obtained using **CL$_s$** prescription

Results

value ± stat ± syst

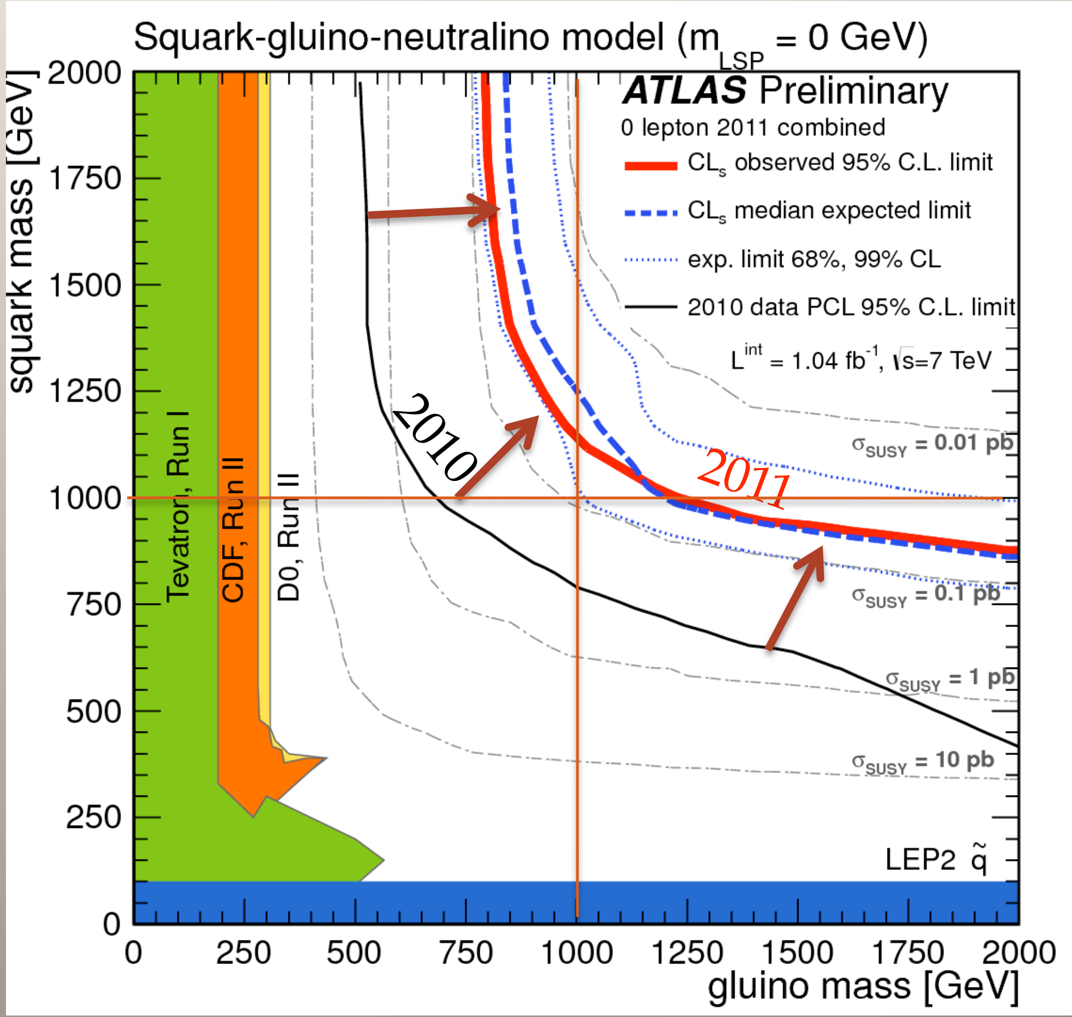
Process	Signal Region				
	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet, m_{eff} > 500 GeV	$\geq$ 4-jet, m_{eff} > 1000 GeV	High mass
Z/γ+jets	32.5 ± 2.6 ± 6.8	25.8 ± 2.6 ± 4.9	208 ± 9 ± 37	16.2 ± 2.1 ± 3.6	3.3 ± 1.0 ± 1.3
W+jets	26.2 ± 3.9 ± 6.7	22.7 ± 3.5 ± 5.8	367 ± 30 ± 126	12.7 ± 2.1 ± 4.7	2.2 ± 0.9 ± 1.2
$t\bar{t}$+ Single Top	3.4 ± 1.5 ± 1.6	5.6 ± 2.0 ± 2.2	375 ± 37 ± 74	3.7 ± 1.2 ± 2.0	5.6 ± 1.7 ± 2.1
QCD jets	0.22 ± 0.06 ± 0.24	0.92 ± 0.12 ± 0.46	34 ± 2 ± 29	0.74 ± 0.14 ± 0.51	2.10 ± 0.37 ± 0.83
Total	62.3 ± 4.3 ± 9.2	55 ± 3.8 ± 7.3	984 ± 39 ± 145	33.4 ± 2.9 ± 6.3	13.2 ± 1.9 ± 2.6
Data	58	59	1118	40	18

- **Model-independent limit** on the *uncorrected* non-SM cross section within our observable signal regions

Process	Signal Region				
	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet, m_{eff} > 500 GeV	$\geq$ 4-jet, m_{eff} > 1000 GeV	High mass
Excluded $\sigma\times$ Acc $\times\varepsilon$ (fb)	24	30	477	32	17

Interpretation: Simple model

- **Three-sparticle model**
  - **Squarks** (two generations, with same mass)
  - **Gluinos**
  - **LSP** (m = 0)
  - m = 5 TeV ∀ other sparticles
- „Perfect“ signature for this analysis
- Other m_{LSP} scenarios to be explored in upcoming paper
  - Low dependence up to ~200 GeV
- Channel with best expected limit chosen for each point
- **Exclusion extending up towards m ~ 1 TeV**



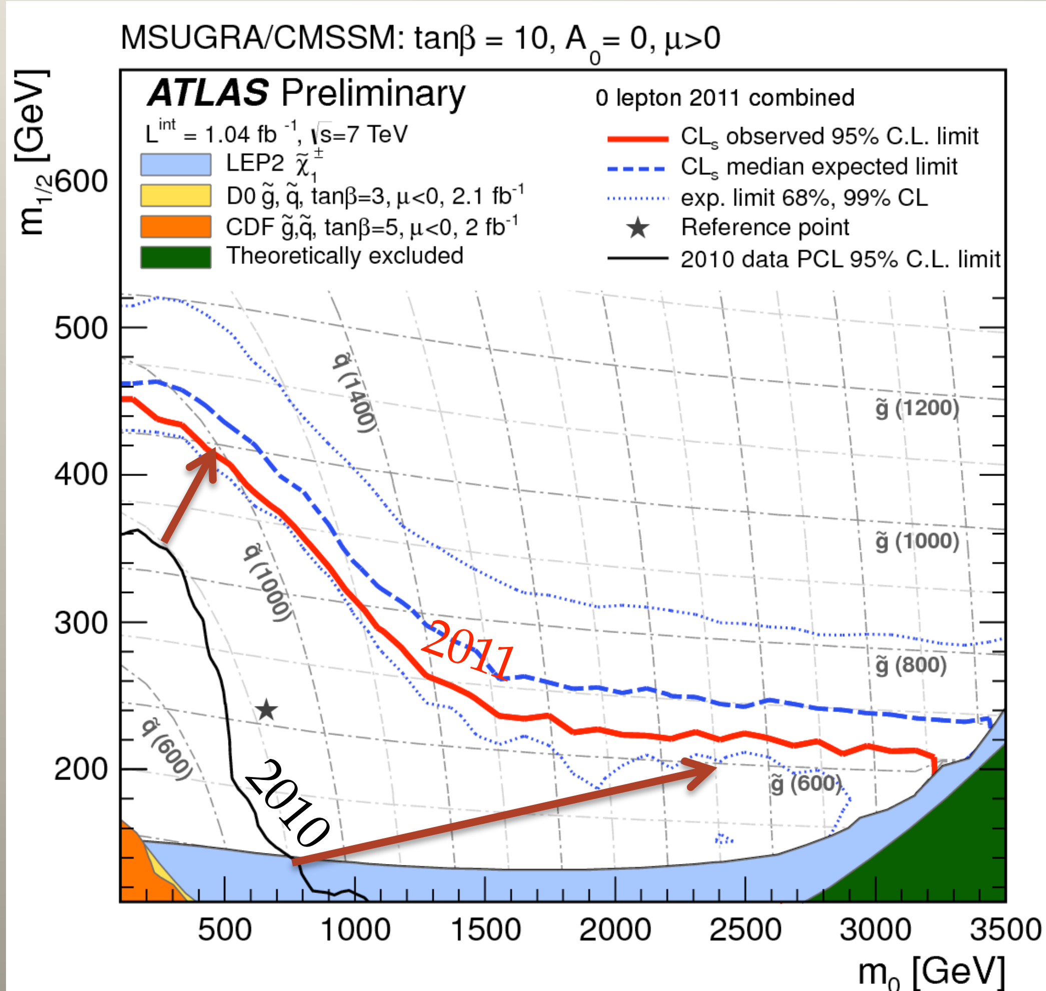
Interpretation: CMSSM/mSUGRA

- $A_0 = 0$
- $\mu > 0$
- $\tan\beta = 10$
- **Easy comparison** to older results

- **Extended reach in m_0** due to new signal regions

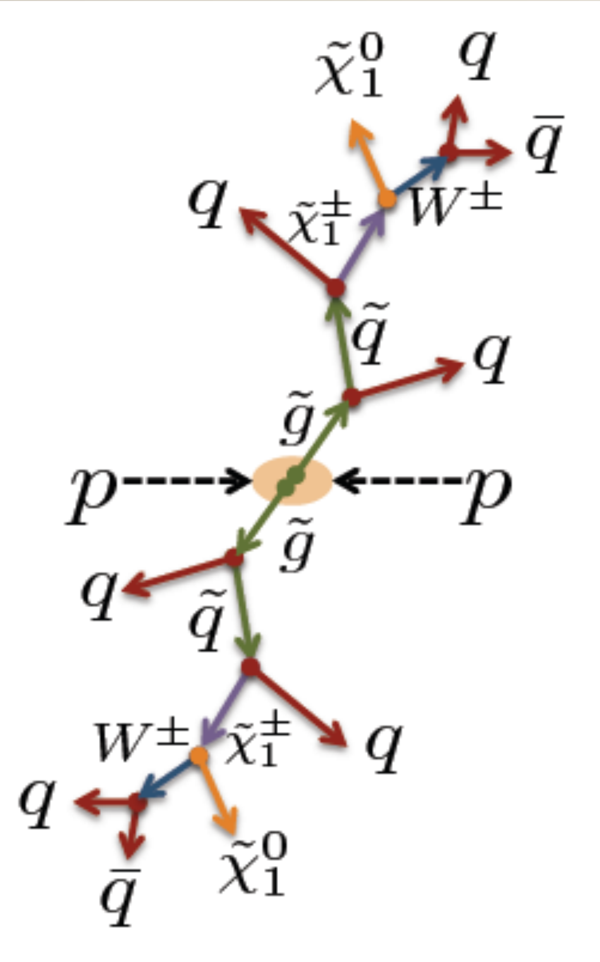
- $m_{1/2} > 450$ GeV at low m_0

- Other model interpretations possible – follow up with information on HEPDATA



6-8 JET ANALYSIS

Large jet multiplicity analysis



- Extension of 2-4 jet analysis
  - Increased sensitivity to **many-body** or **cascade decays**
  - Example: **high** m_0 region in CMSSM/mSUGRA
- Signature: **>6 to >8 jets + MET** + lepton veto
  - QCD modelling is **the** issue
  - We cannot expect a good MC prediction => **Entirely data-driven approach**

MET/$\sqrt{H_T}$

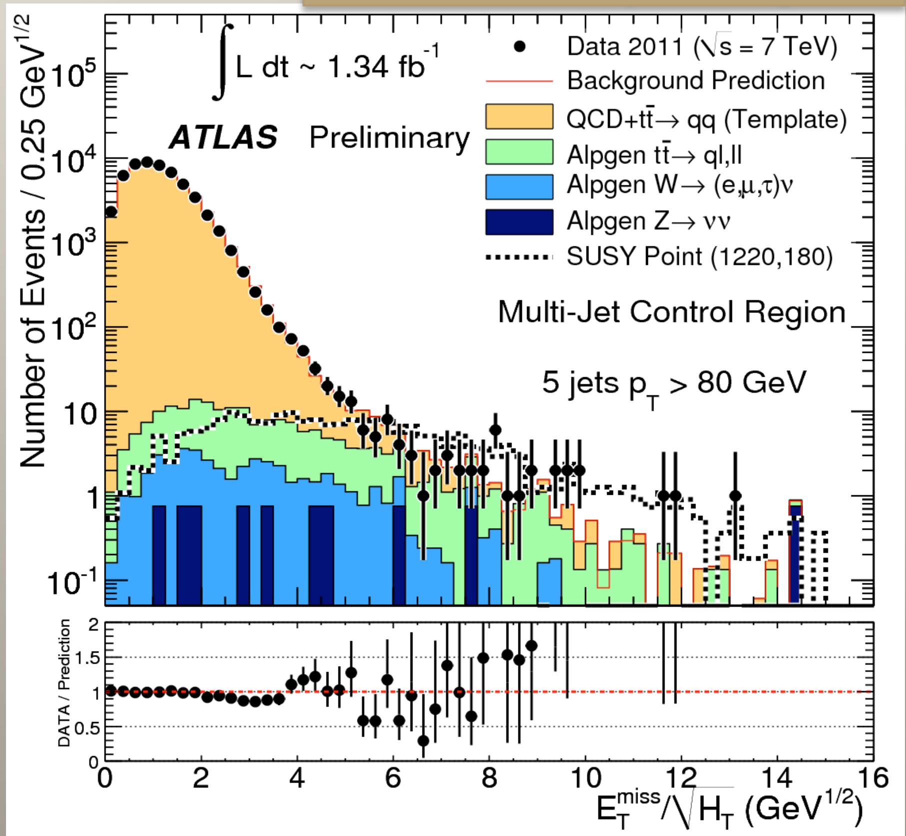
(including fully hadronic tt)

- MET resolution dominated by **stochastic fluctuations**

$$\sigma^2(E_T^{miss}) \sim H_T = \sum p_T^{jet}$$

- Use **MET/$\sqrt{H_T}$** to **remove MC simulation dependence**
  – Nearly independent of jet multiplicity and pile-up
  – Cut on this, and **no other MET variables**

5 jet selection compared with 4 jet template



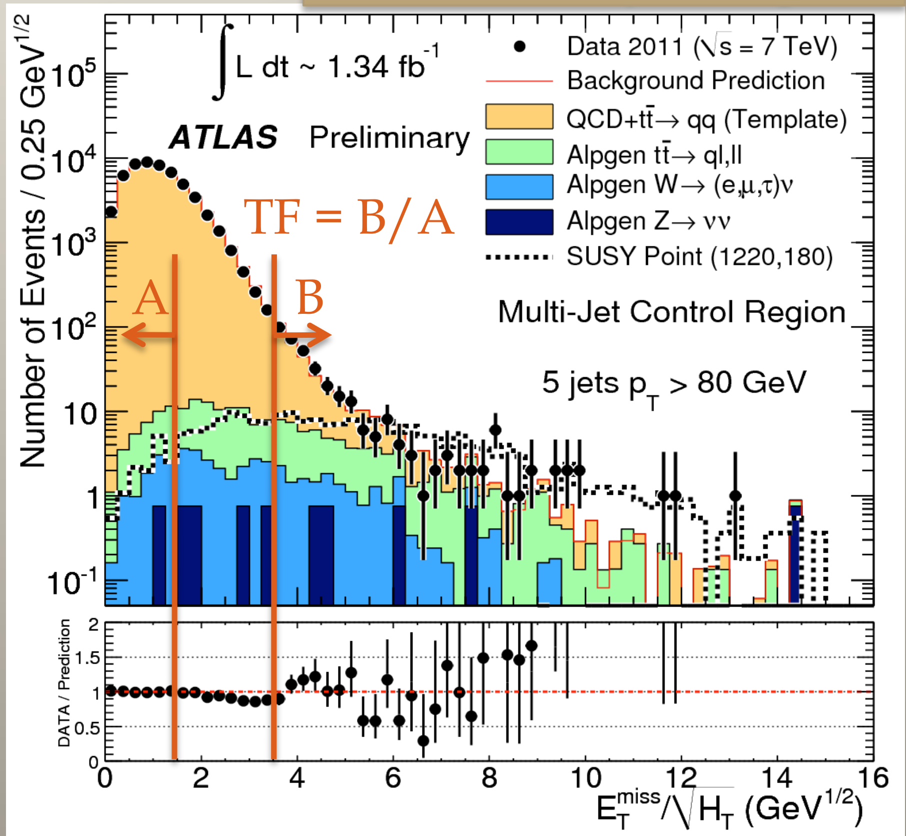
MET/$\sqrt{H_T}$

(including fully hadronic tt)

- Control Region with **MET/$\sqrt{H_T}$ < 1.5 $\sqrt{\text{GeV}}$**
- Transfer Factor from events with exactly 5 or 6 jets

- **Systematic cross-checks**:
  - MET/$\sqrt{H_T}$ invariance tested using lower-multiplicity selections
  - Jet smearing, as in 2-4 jet analysis
  - Jet flavour separation
  - Special study of LAr readout-problem region

5 jet selection compared with 4 jet template



Signal Region selection

- **Multi-jet triggers**, requiring 4 or 5 jets
  - => Lower leading jet threshold
- **MET/$\sqrt{H_T}$** replaces MET and MET/m_{eff}
  - $\Delta\phi$(jet, MET)$_{min}$ also removed
- **LAr readout problem =>** Jet energy correction in affected region, event vetoed if MET correction is large (>10 GeV and >10% of MET)

Signal region	7j55	8j55	6j80	7j80
Jet p_T	$>55\,\mathrm{GeV}$		$>80\,\mathrm{GeV}$	
Jet $\lvert\eta\rvert$	<2.8			
ΔR_{jj}	>0.6 for any pair of jets			
Number of jets	≥ 7	≥ 8	≥ 6	≥ 7
$E_T^{miss}/\sqrt{H_T}$	$>\ 3.5\ \mathrm{GeV}^{1/2}$			

Trigger plateau

SR definition

BG reduction and control

$$\int L\,dt = 1.34\ \mathrm{fb}^{-1}$$

$$H_T = \sum_{\text{Jets}} p_T$$

$(p_T > 40\ \mathrm{GeV}, |\eta| < 2.8)$

Top and other backgrounds

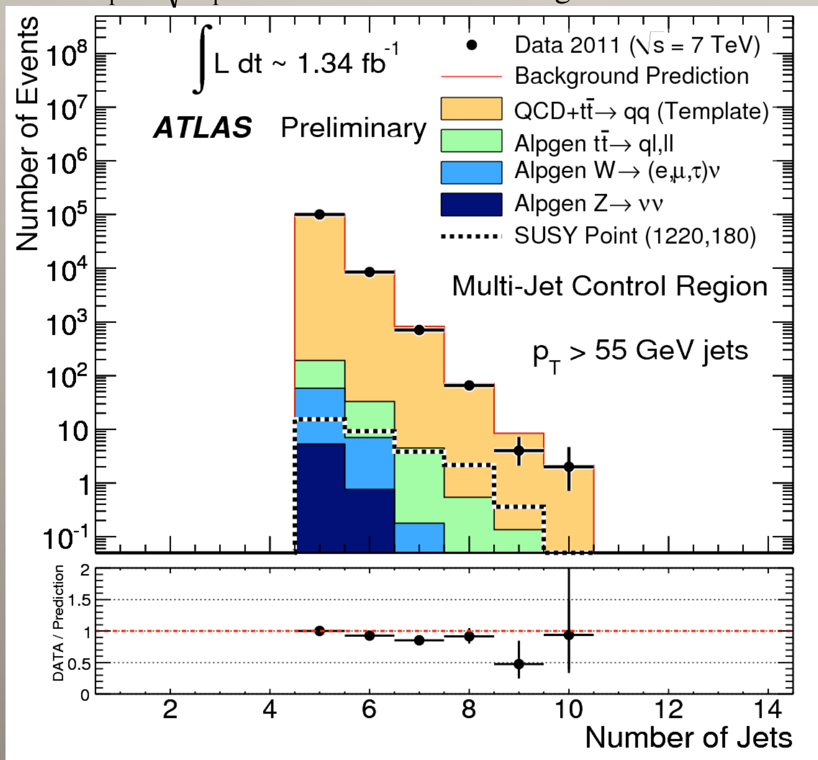
(Semi- and fully leptonic tt, W/Z + jets)

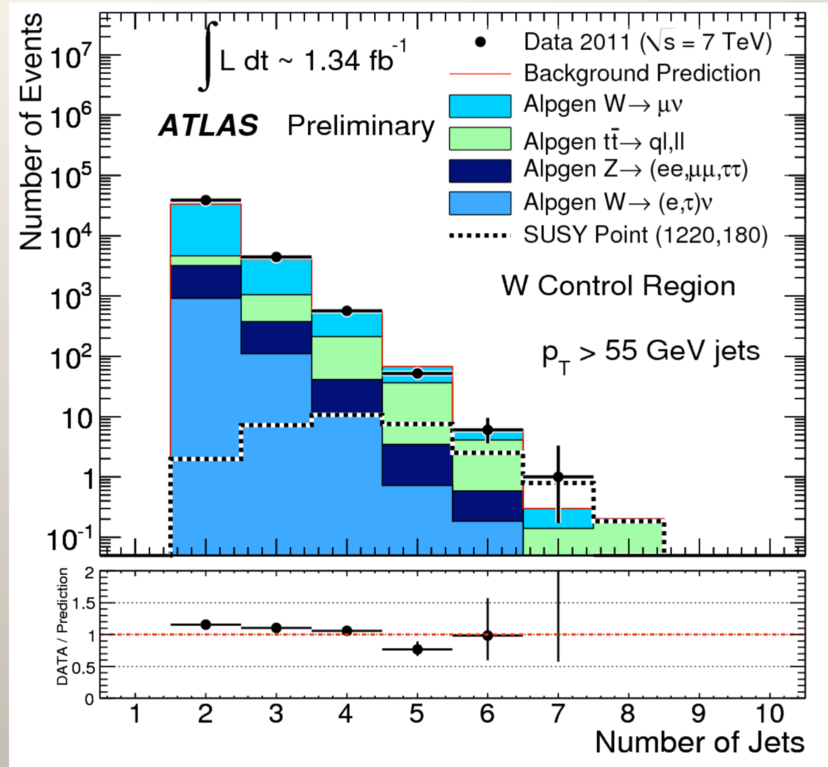
- **Top**: (Second largest background)
  - **Control Region**: 1 muon, $40 < m_T < 100$ GeV, b-tagged jet
    - SR jet cuts applied, treating muon as a jet
  - **Transfer Factors** from simulation (ALPGEN)
    - Systematic uncertainties estimated as in 2-4 jet analysis
  - **Validation Regions (VRs)** vary jet p_T and MET/$\sqrt{H_T}$ cuts
- **W/Z+jets** are small:
  - Estimated from **simulation**, due to low CR statistics
  - Validation Regions show no problems
    - W: Like top, but b-jet veto
    - Z: Two muon VR selection

Validation Regions

- Use **4 & 5 jet Validation Regions**, extending out in N_{jet} as far as statistics allow

$1.5 < E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{H_{\mathrm{T}}} < 2.0\ \sqrt{\mathrm{GeV}}$ Control Region





- **Jet multiplicity** tested in events with and without leptons
- Scaling of the number of jets **is understood**
- Also agreement with other theoretical cross-checks

Results

Signal region	7j55	8j55	6j80	7j80
Multi-jets	26 ± 5.2	2.3 ± 0.7	19 ± 4	1.3 ± 0.4
$t\bar{t} \to \ell(\ell)X$	10.8 ± 6.7	$0^{+4.3}$	6.0 ± 4.6	$0^{+0.13}$
W + jets	0.95 ± 0.80	$0^{+0.13}$	0.34 ± 0.34	$0^{+0.13}$
Z + jets	$1.5^{+1.8}_{-1.5}$	$0^{+0.75}$	$0^{+0.75}$	$0^{+0.75}$
Total SM	$39.3^{+8.7}_{-8.5}$	$2.3^{+4.4}_{-0.7}$	25.8 ± 6.1	$1.3^{+0.9}_{-0.4}$
Data	45	4	26	3
$N^{95\%}_{\mathrm{BSM,max}}$	26.0	11.2	16.3	6.0
$(\sigma^{95\%}_{\mathrm{BSM,max}} \times \epsilon)/\mathrm{fb}$	19.4	8.4	12.2	4.5
p_{SM}	0.30	0.36	0.49	0.16

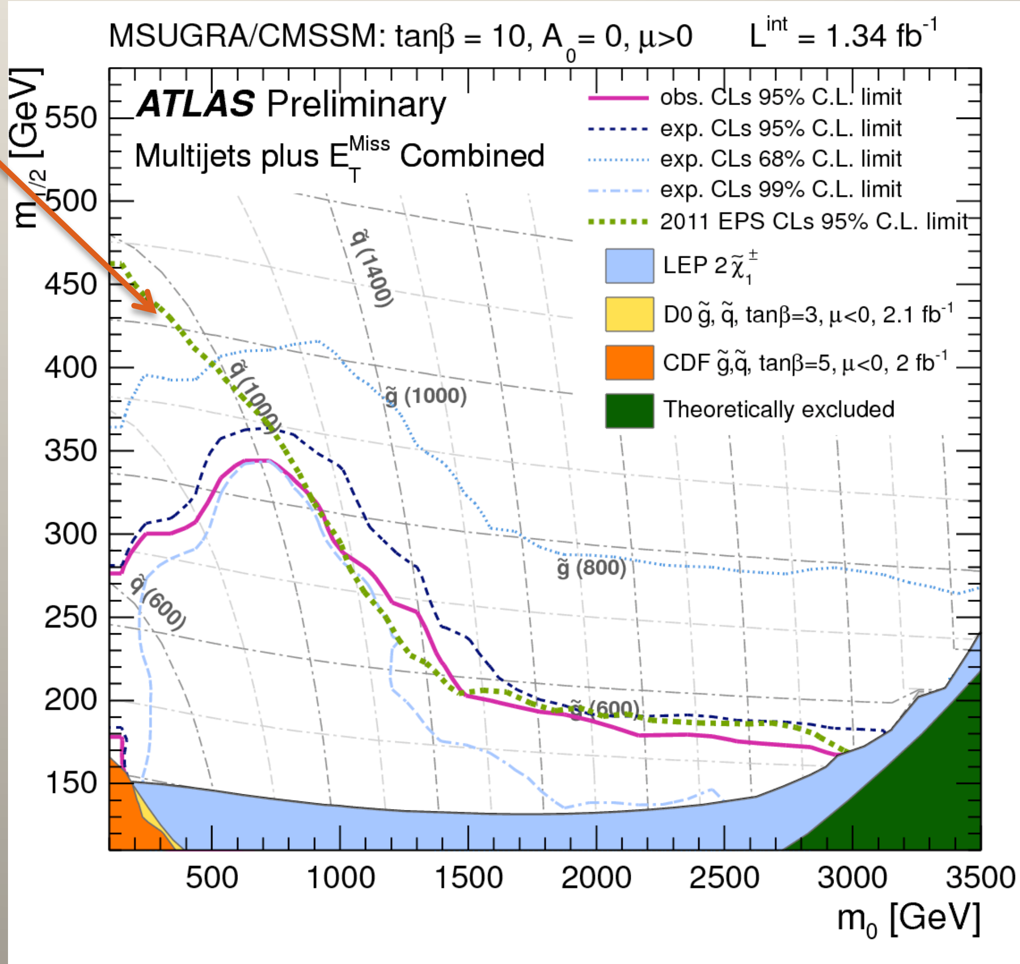
- No excess seen => set limits
- N and σ are **model-independent upper limits** on non-SM processes after all selection
  - Still using **$\mathrm{CL_s}$** prescription

Example interpretation: CMSSM

Exclusion from
2-4 jet analysis

- Reminder: $A_0 = 0$, $\mu > 0$, $\tan\beta = 10$
- Channel with best expected limit chosen for each point
- Upward fluctuations in two key channels => exclusion less than predicted

$m_{\tilde{g}} > 520$ **GeV**



Conclusion

- The search reach in jets+MET final states has been **dramatically extended**
  - **2-4 jet** and **6-8 jet** inclusive multiplicities
  - **~1 fb^{-1}** of data & analysis improvements
  - Negative results interpreted using simplified *R*-parity conserving SUSY model and CMSSM
  - Mass reach at or approaching 1 TeV
- Papers are in preparation for these analyses

If you want more...

BACKUP

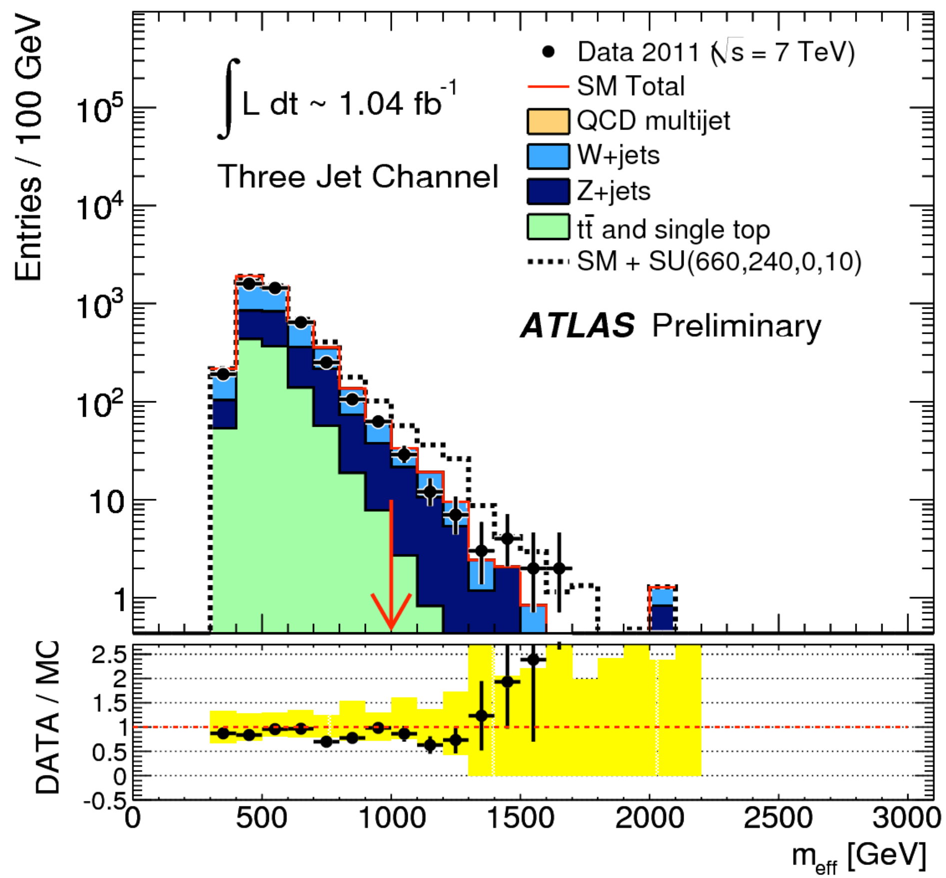
Statistical methods

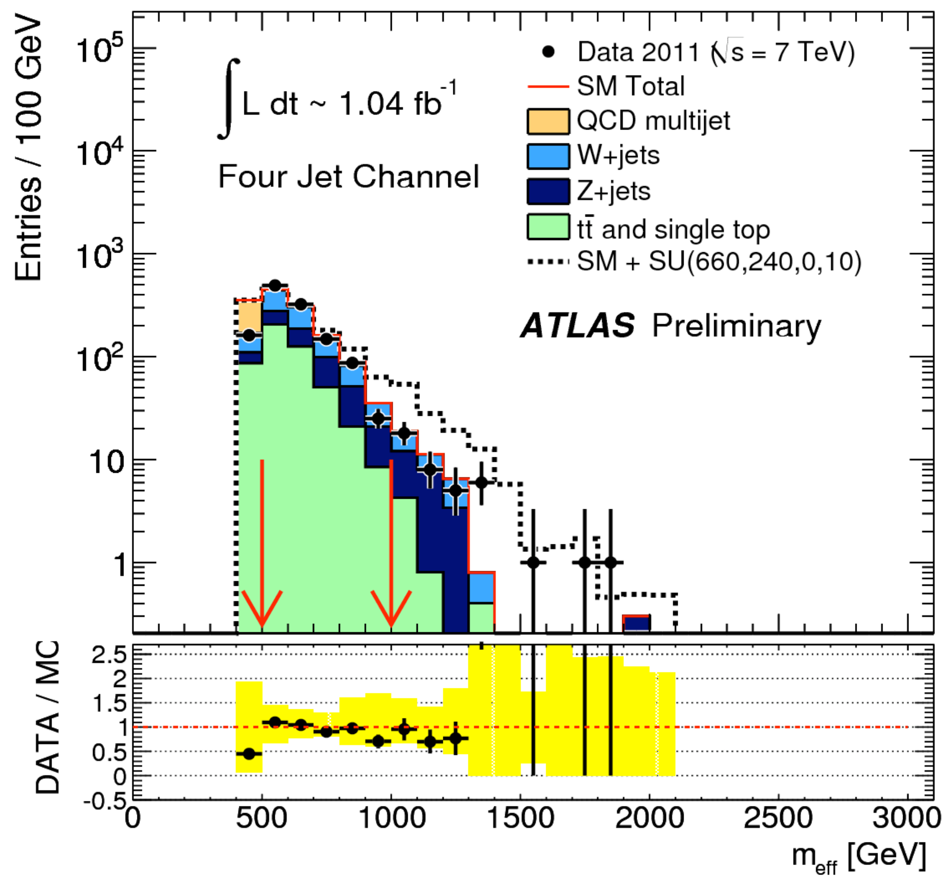
- Simultaneous likelihood fit to Signal Region + 5 Control Regions in each channel
  - Six Poisson-distributed variables and PDF to constrain systematic uncertainties

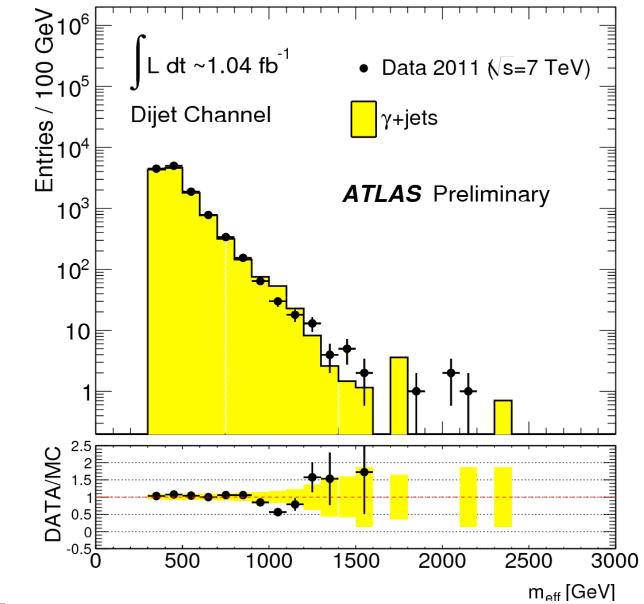
$$L(n \mid \mu, b, \theta) = P_{\mathrm{SR}} \times P_{\mathrm{WR}} \times P_{\mathrm{TR}} \times P_{\mathrm{ZRa}} \times P_{\mathrm{ZRb}} \times P_{\mathrm{QR}} \times C_{\mathrm{syst}}$$

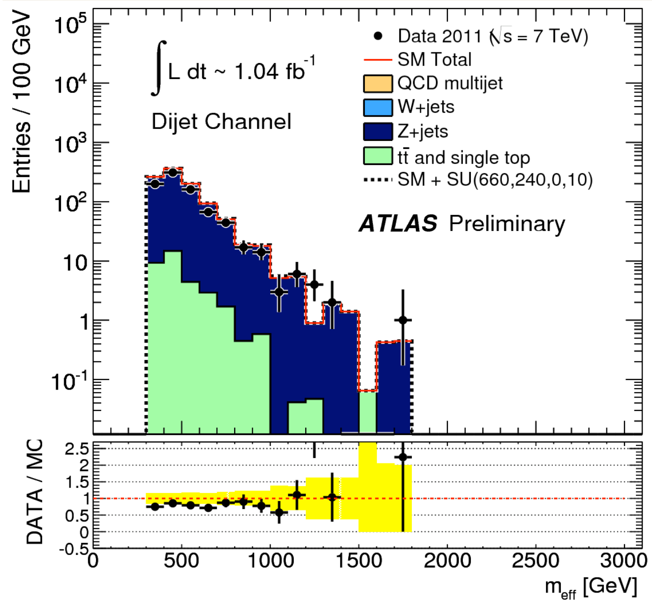
- Correlations between Control Regions taken into account
  - eg jet energy scale and b-tagging efficiency

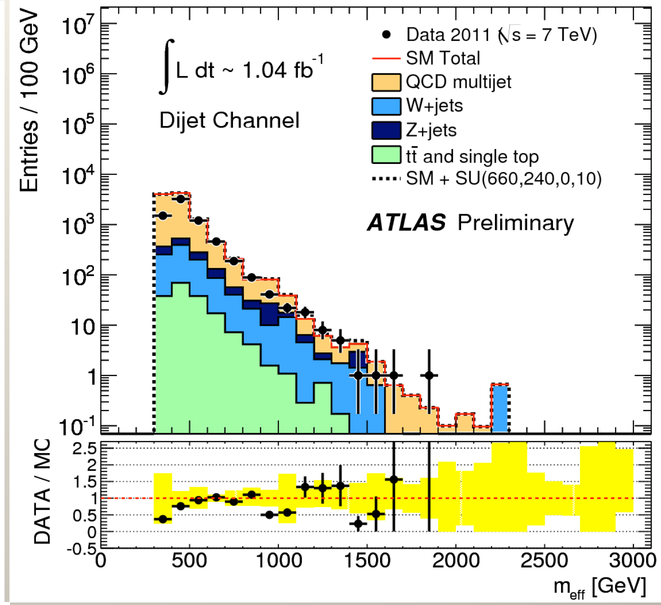
Signal Region observations

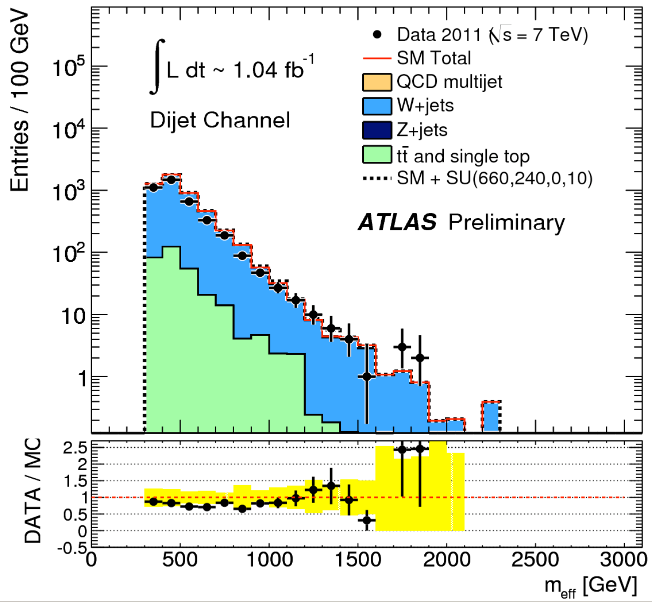


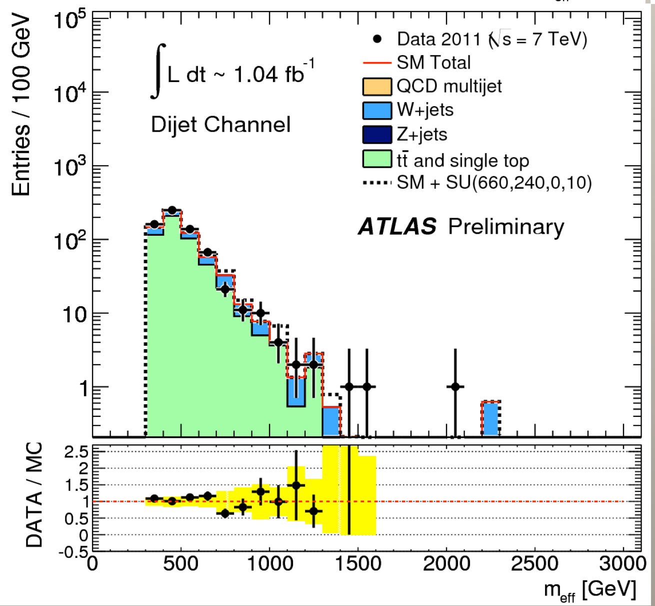




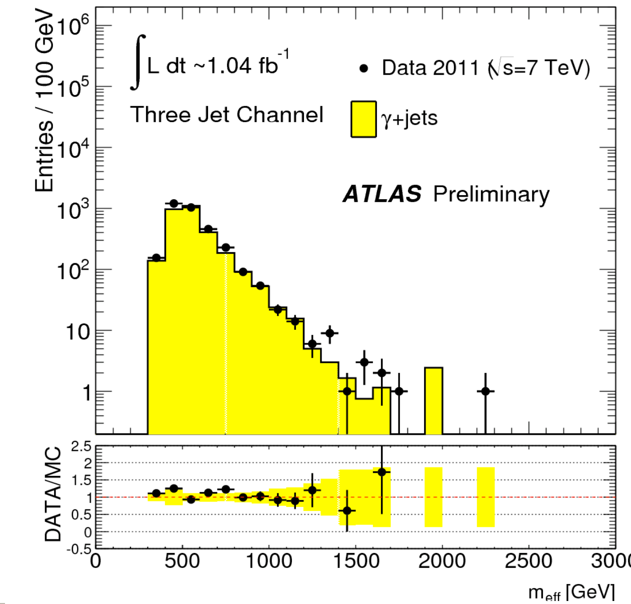


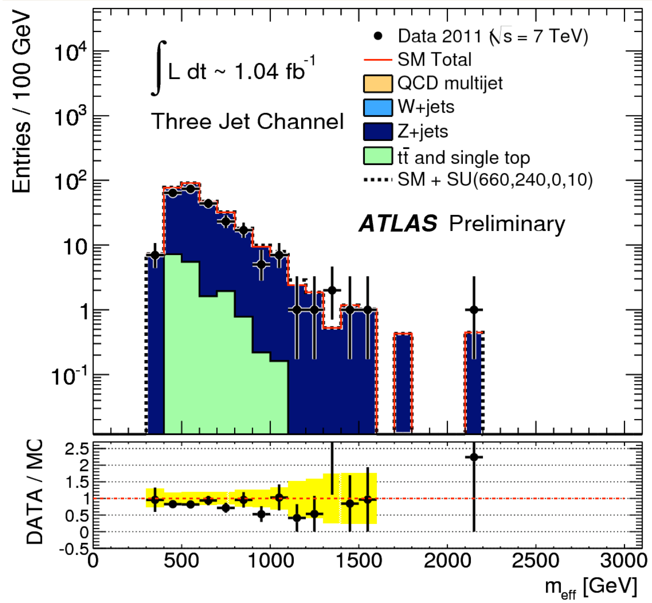


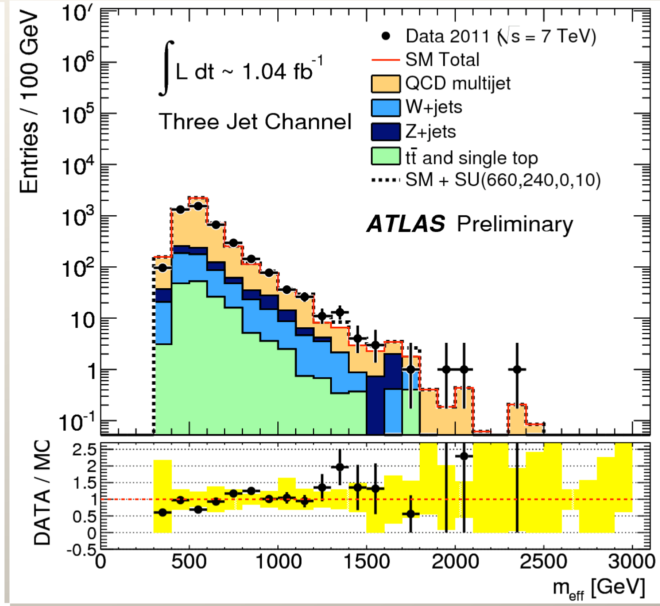


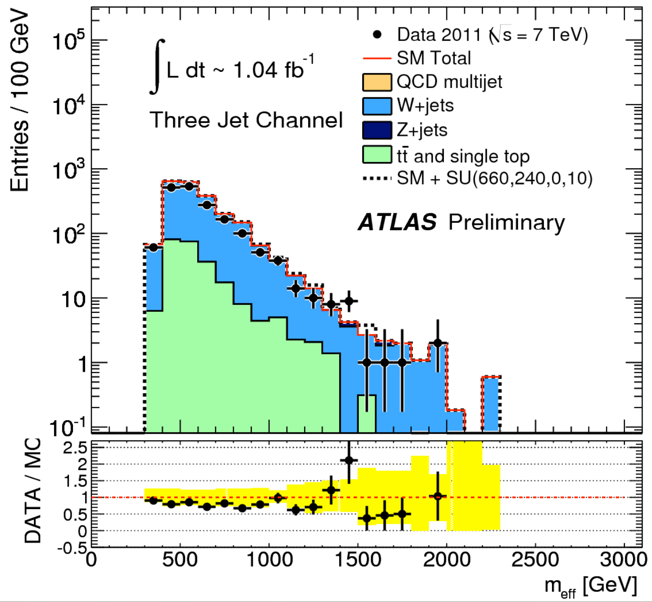


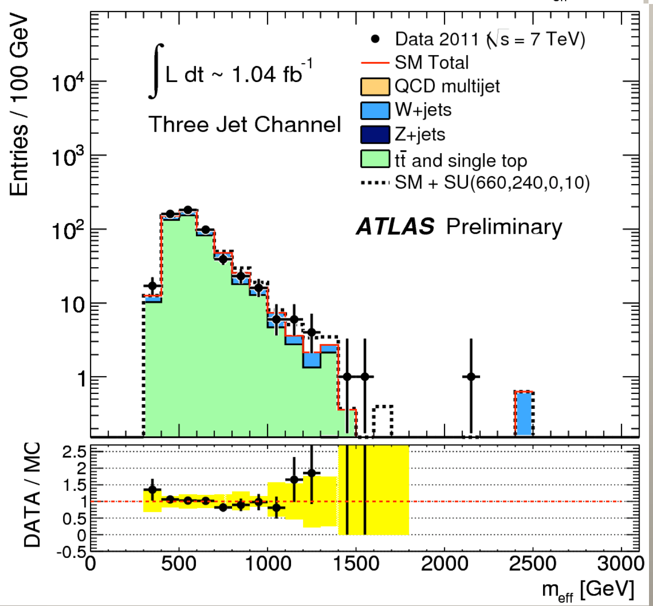
Dijet channel Control Regions



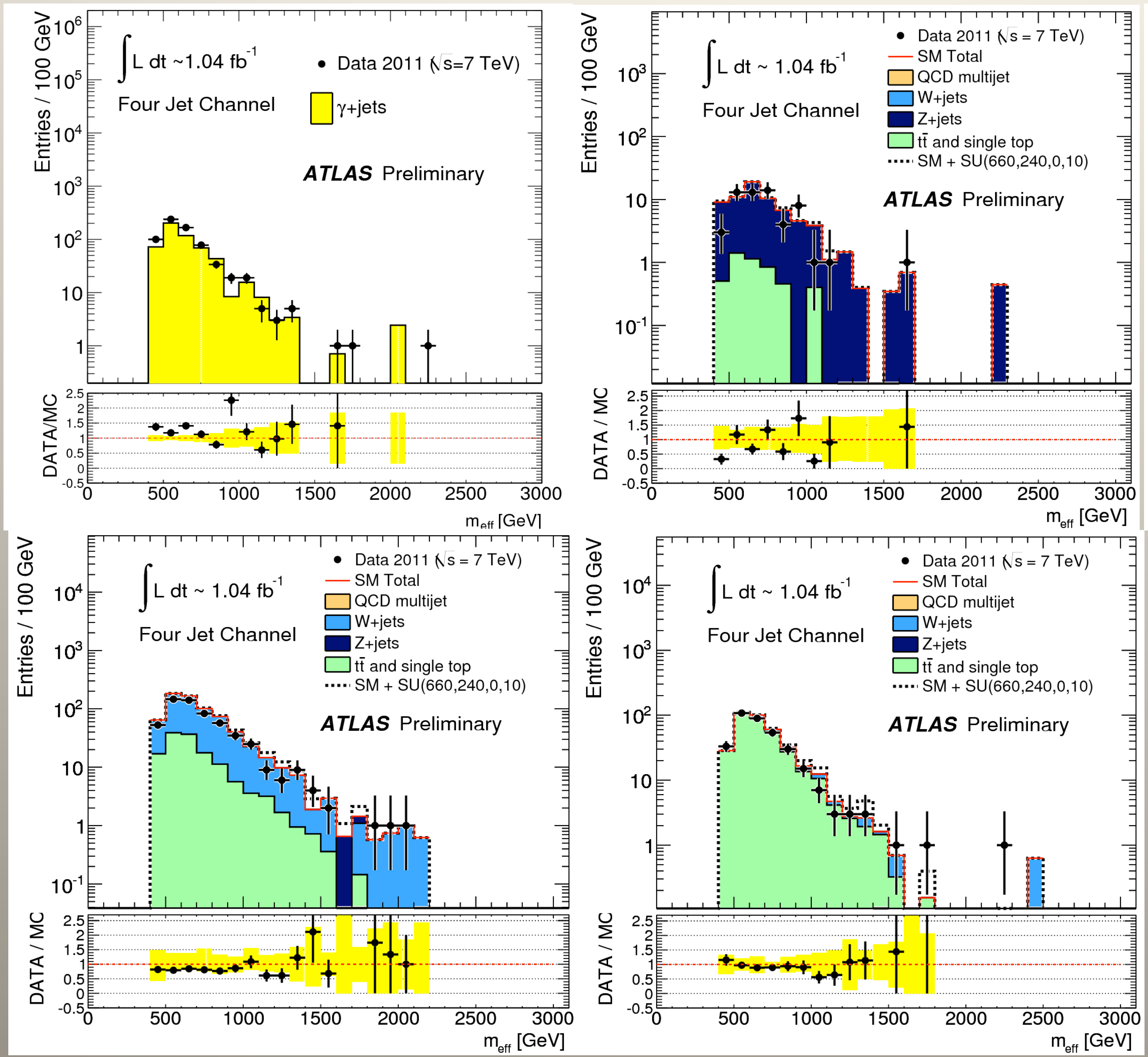




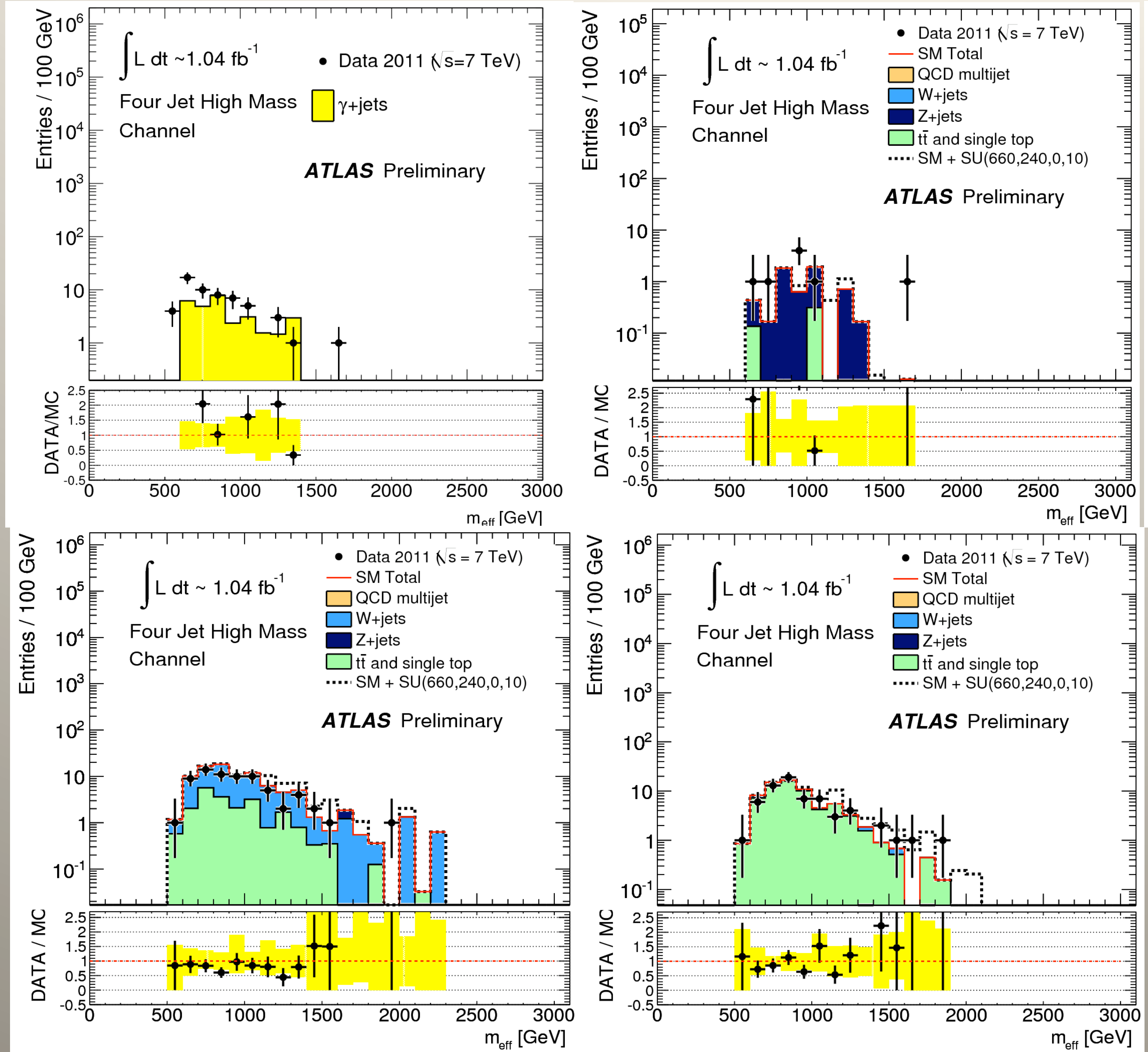




Three jet channel Control Regions

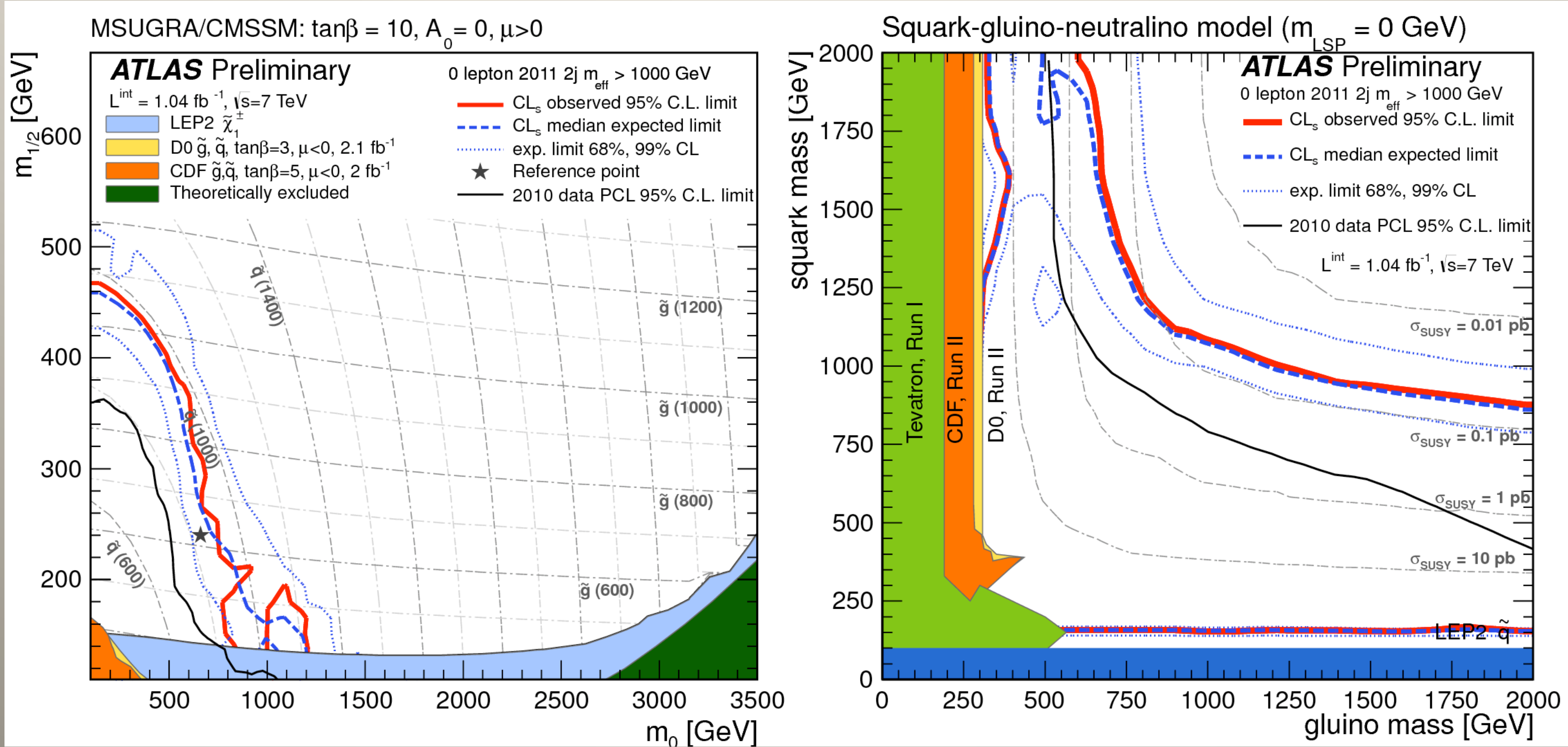


Four jet channel Control Regions

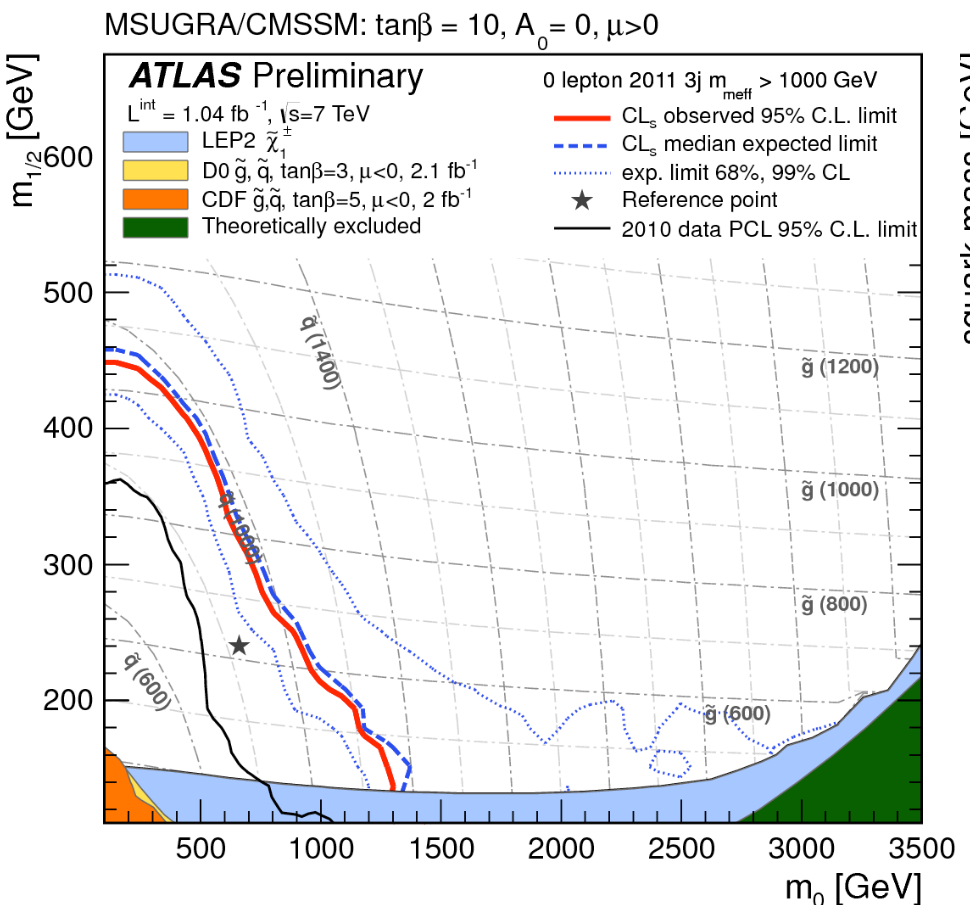


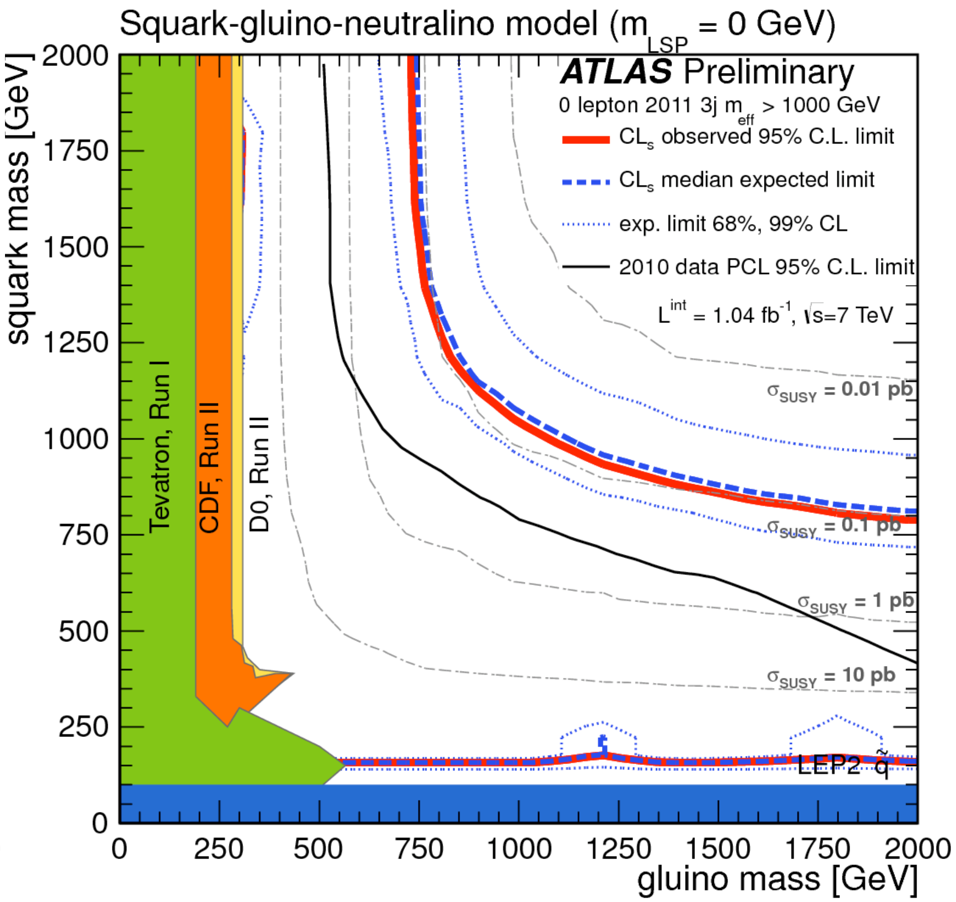
Four jet high mass channel Control Regions

Dijet channel exclusion

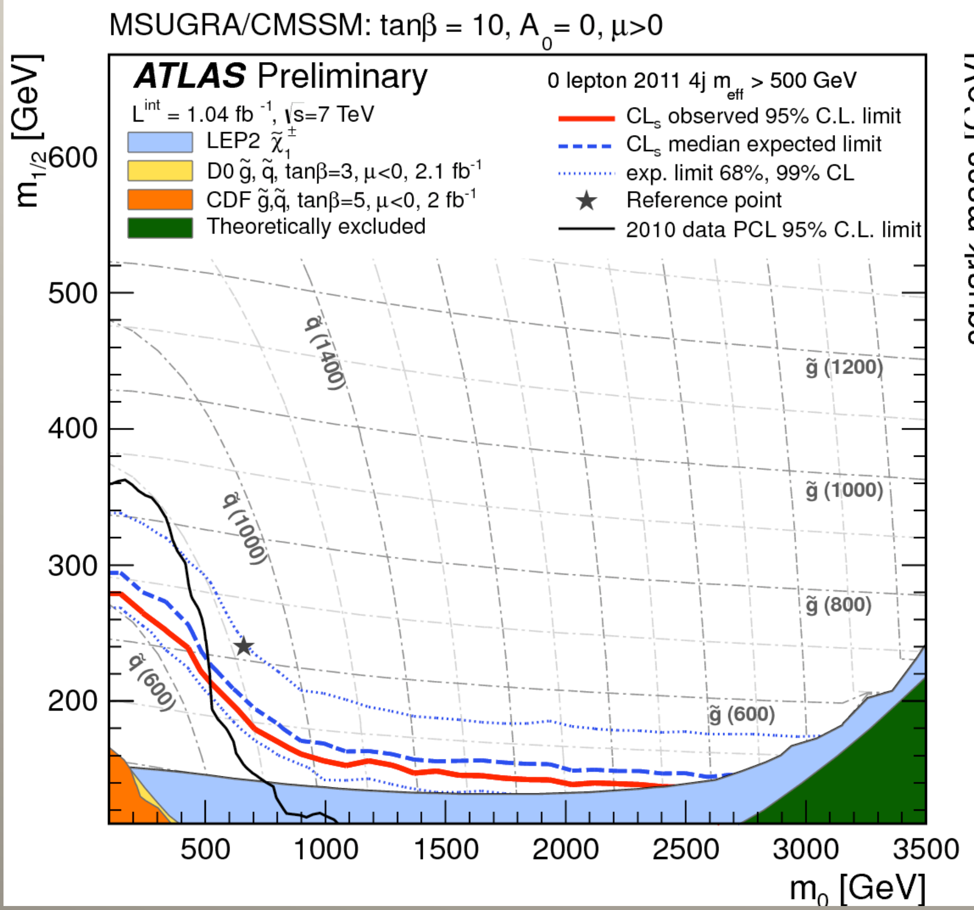


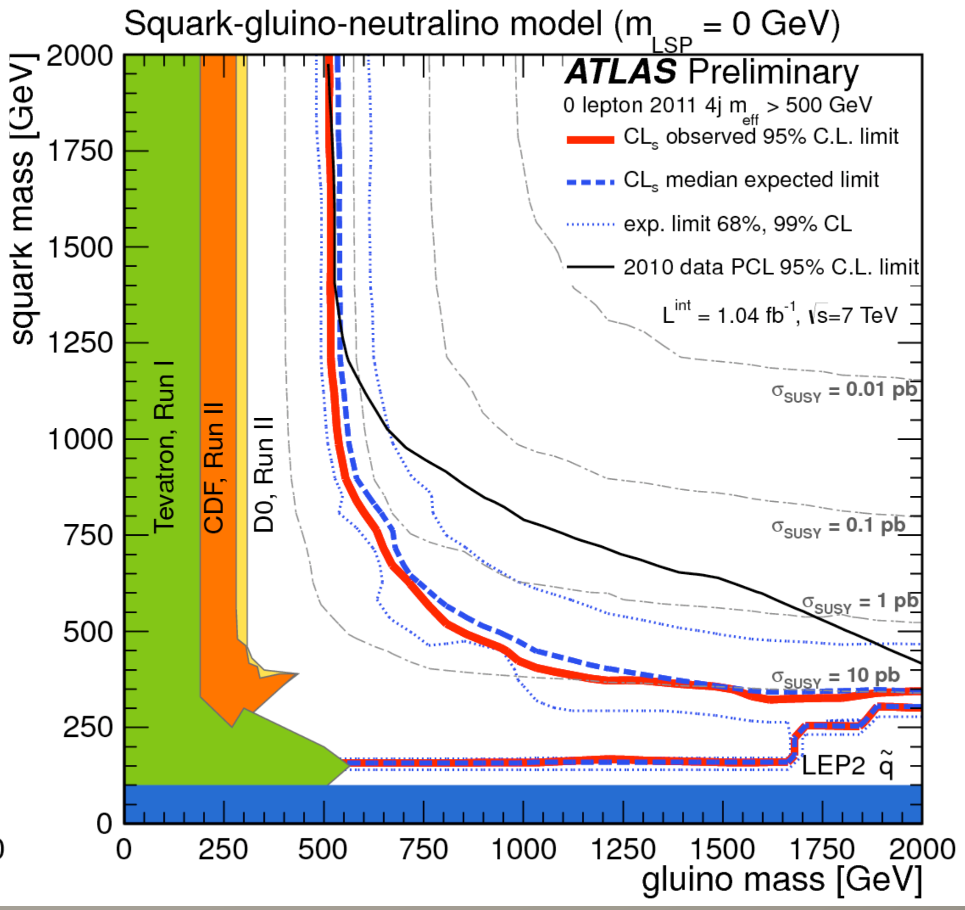
Three jet channel exclusion



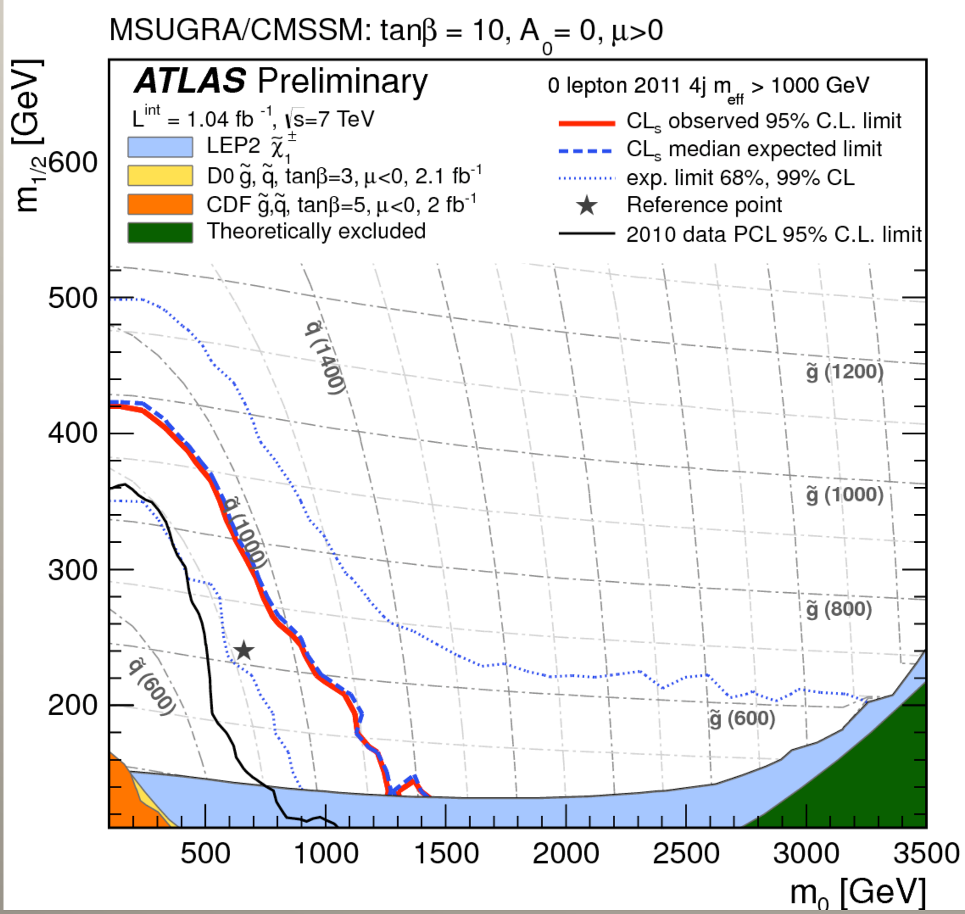


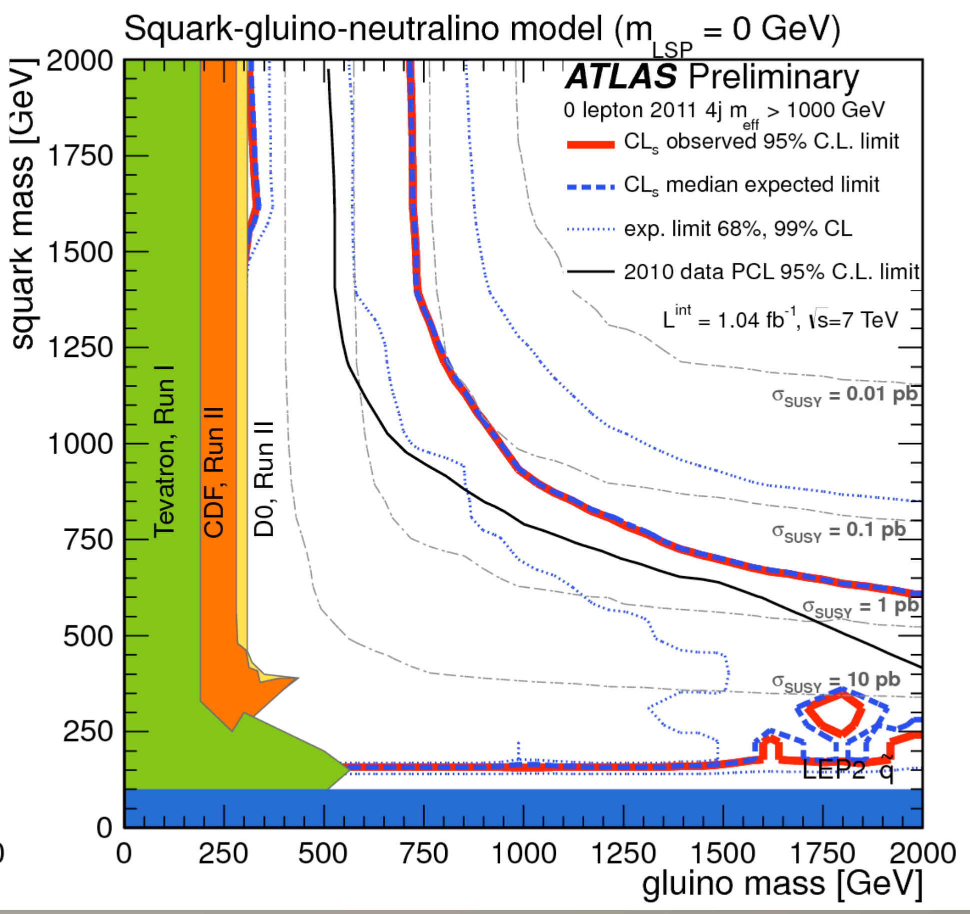
Four jet channel exclusion (m_{eff} > 500 GeV)



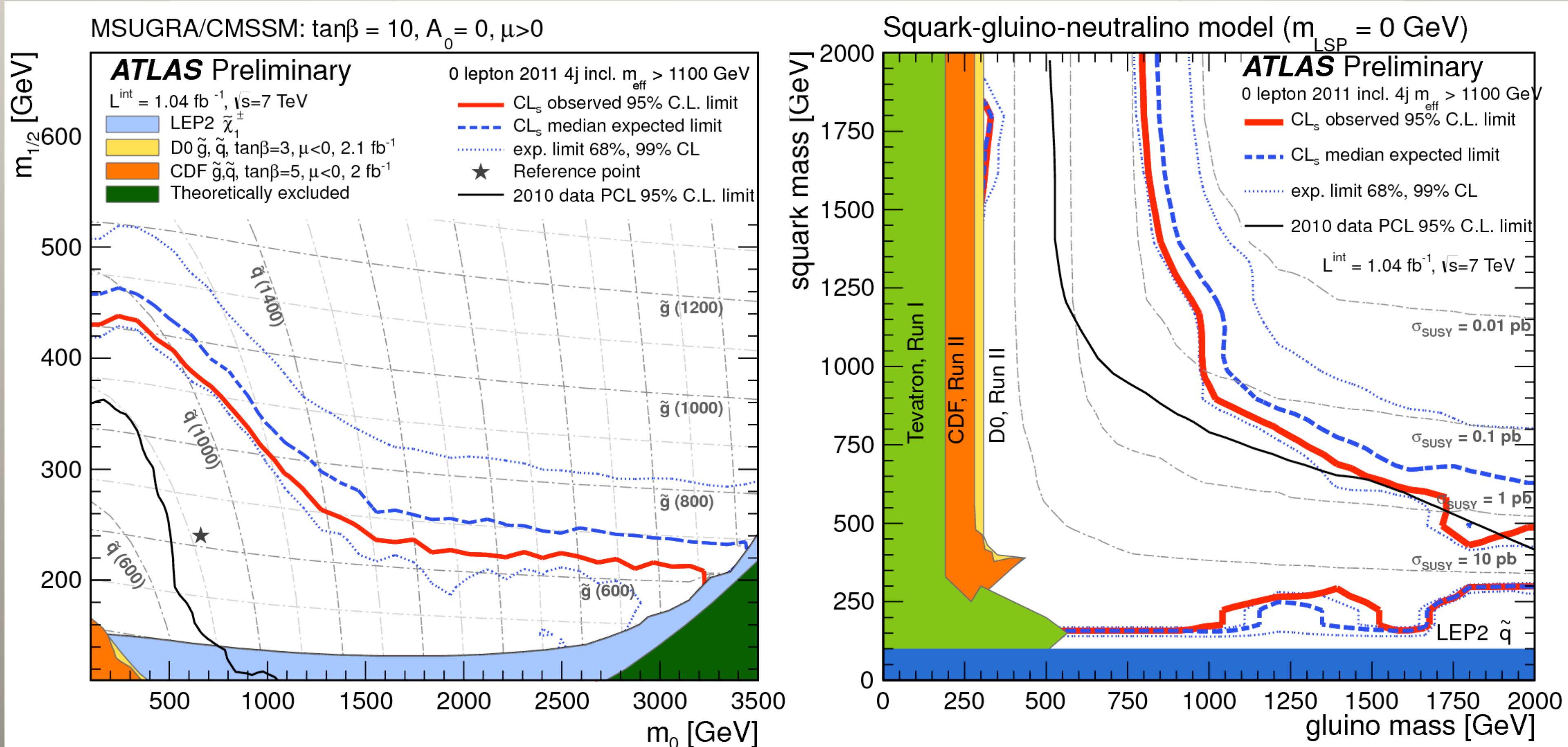


Four jet channel exclusion (m_{eff} > 1000 GeV)

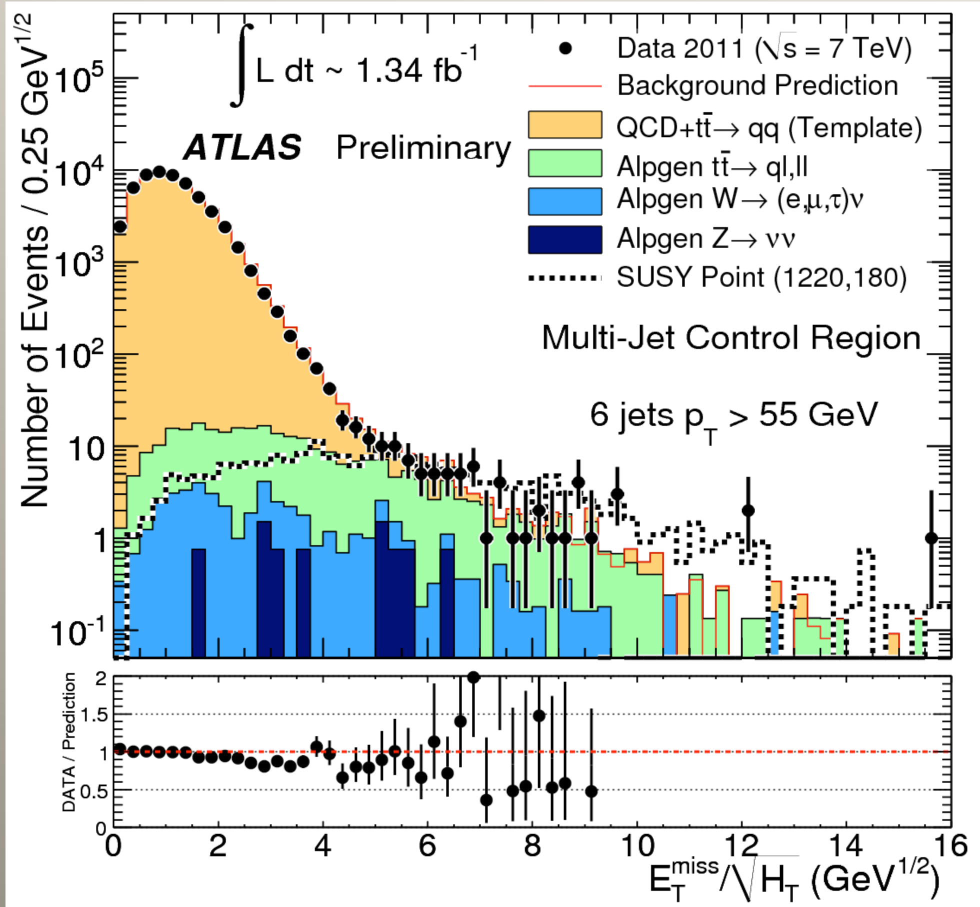


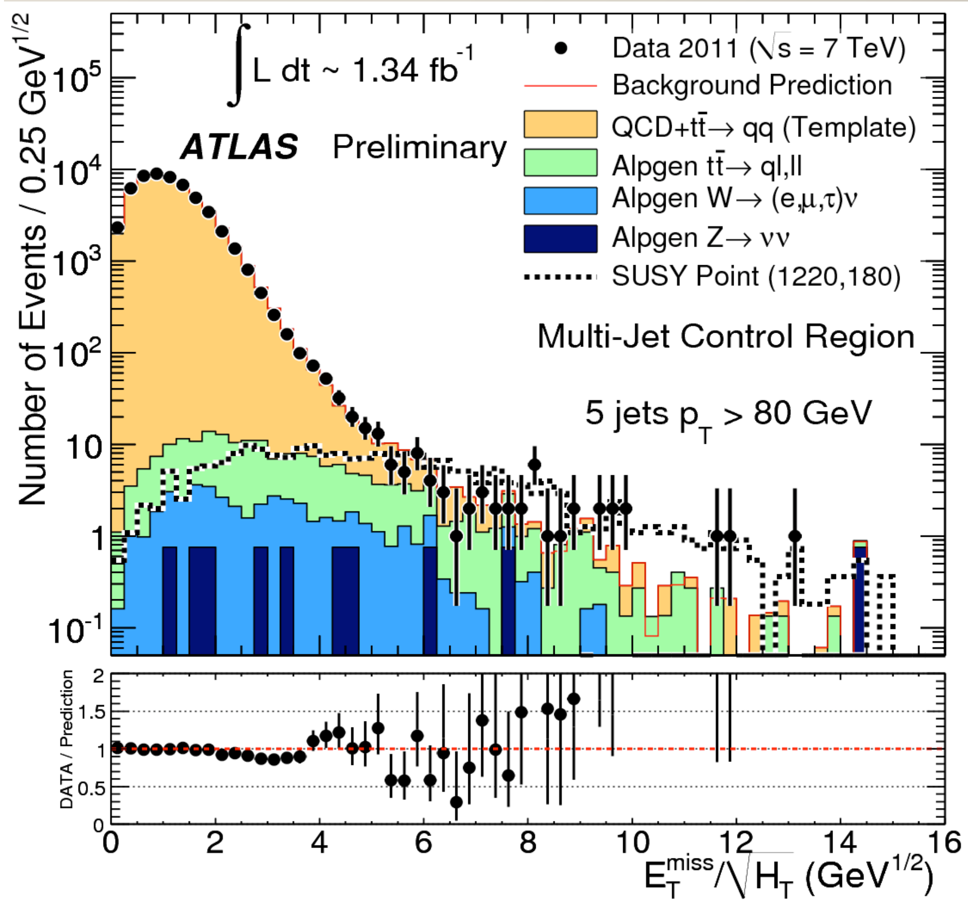


Four jet high mass channel exclusion

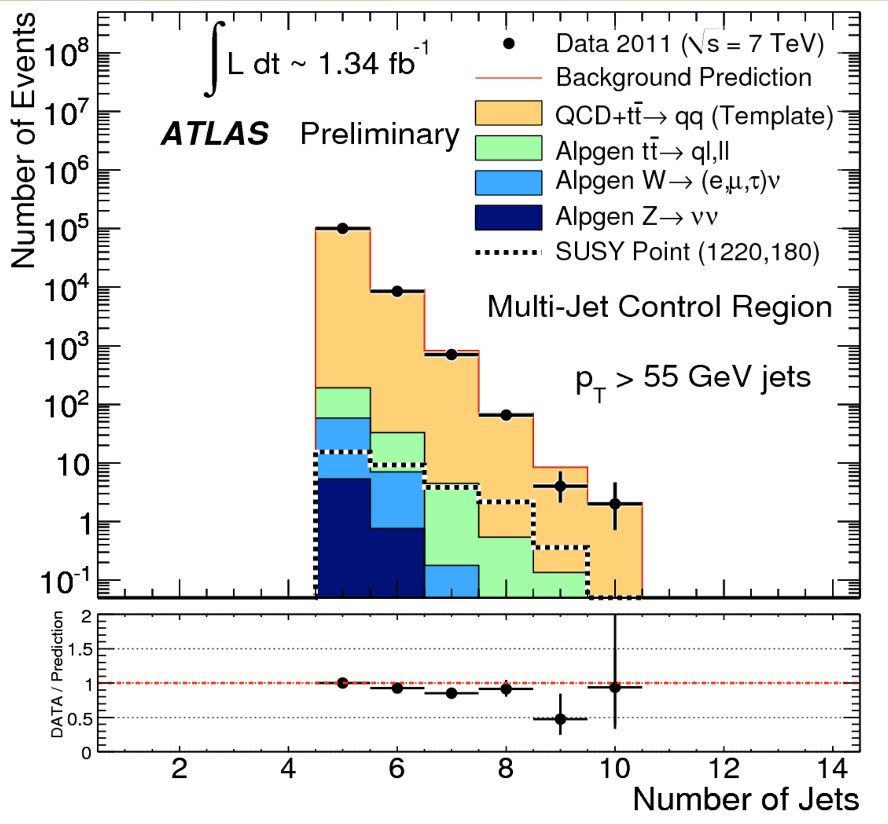


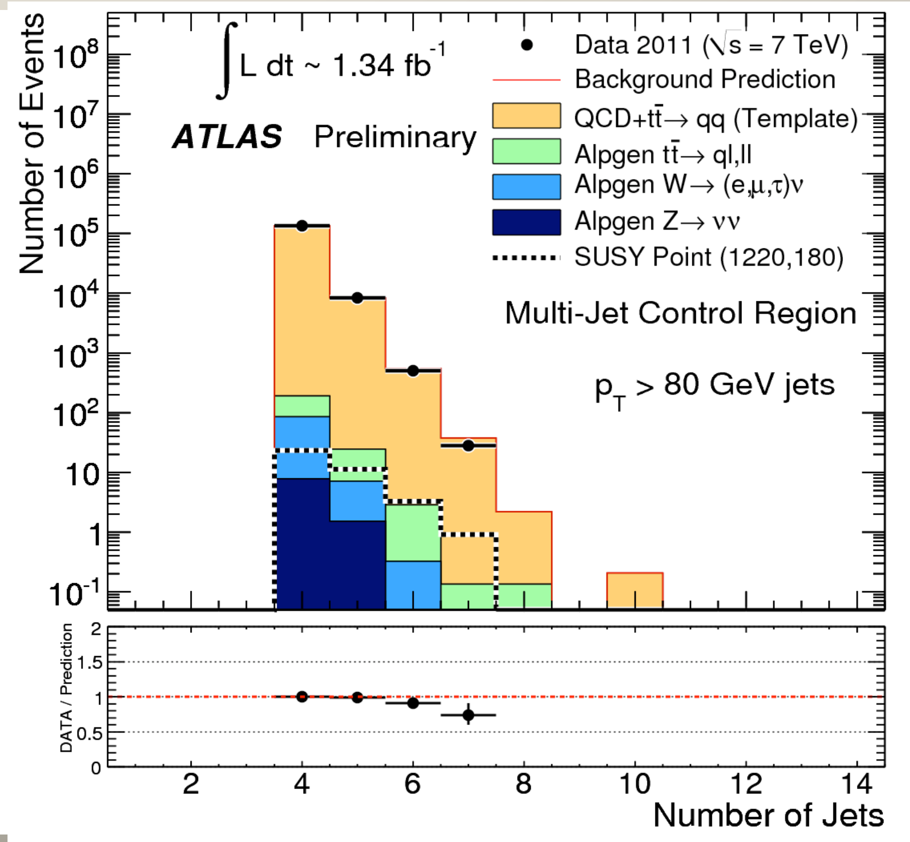
MET/$\sqrt{H_T}$ validation



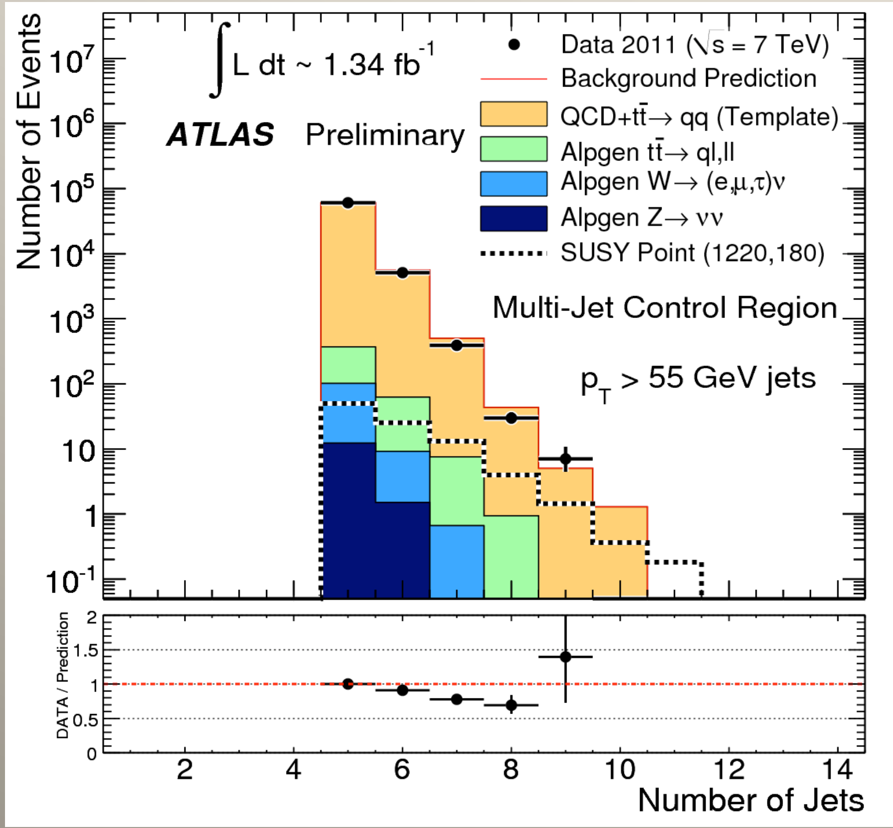


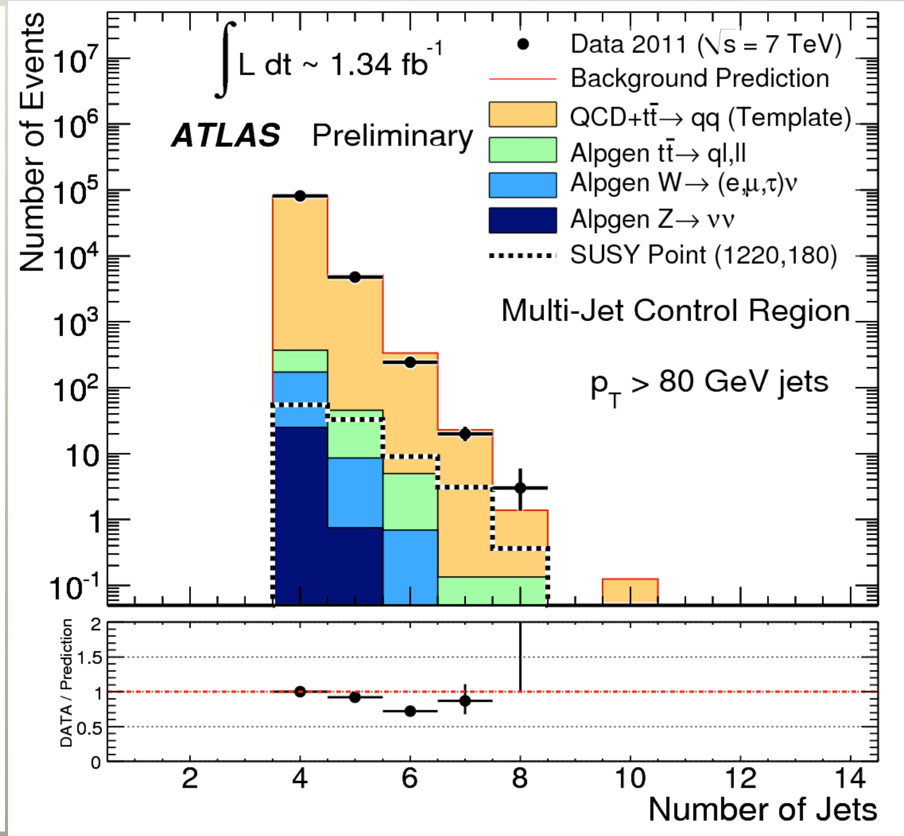
Jet multiplicity: $1.5 < \mathrm{MET}/\sqrt{H_T} < 2.0\ \sqrt{\mathrm{GeV}}$



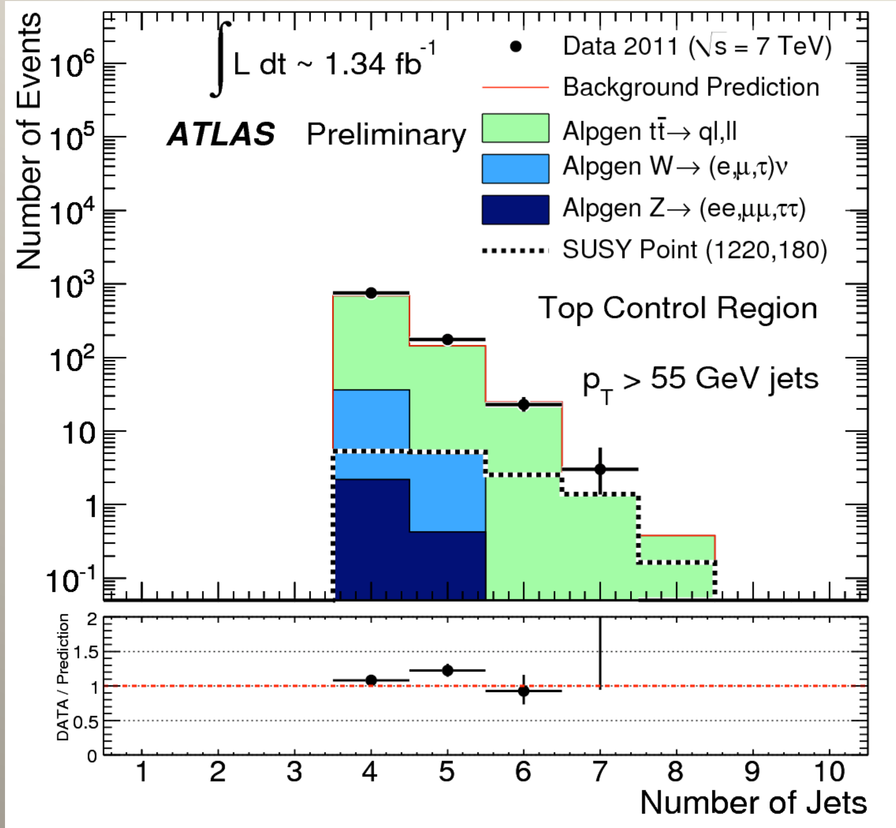


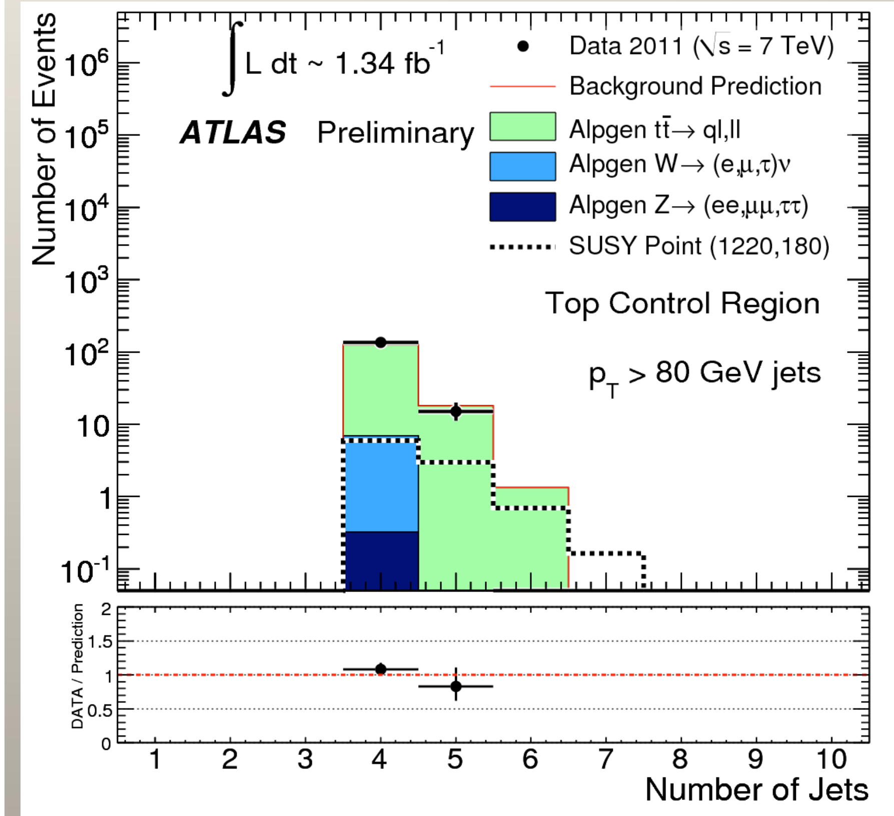
Jet multiplicity: $2.0 < \mathrm{MET}/\sqrt{H_T} < 3.0\ \sqrt{\mathrm{GeV}}$



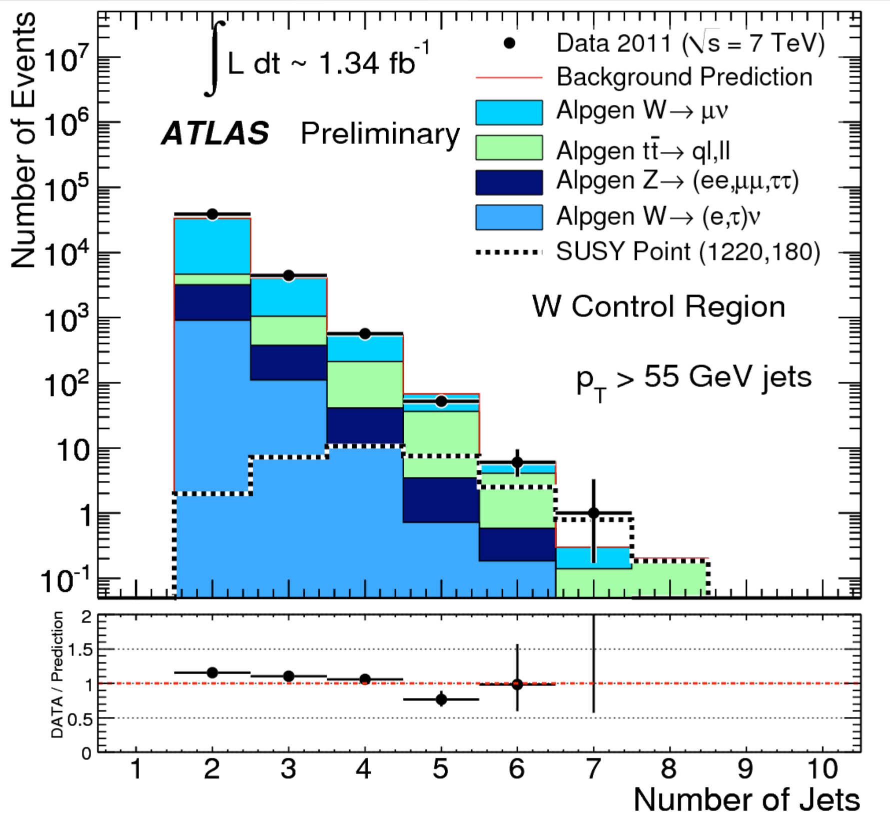


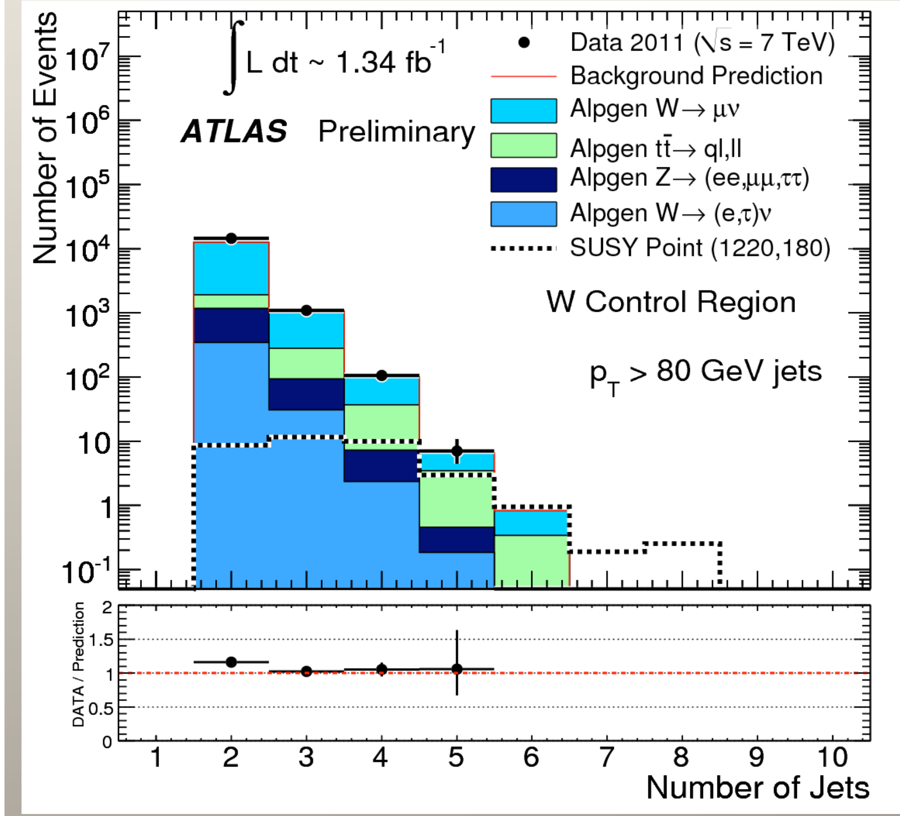
Multijets: Top Validation Region



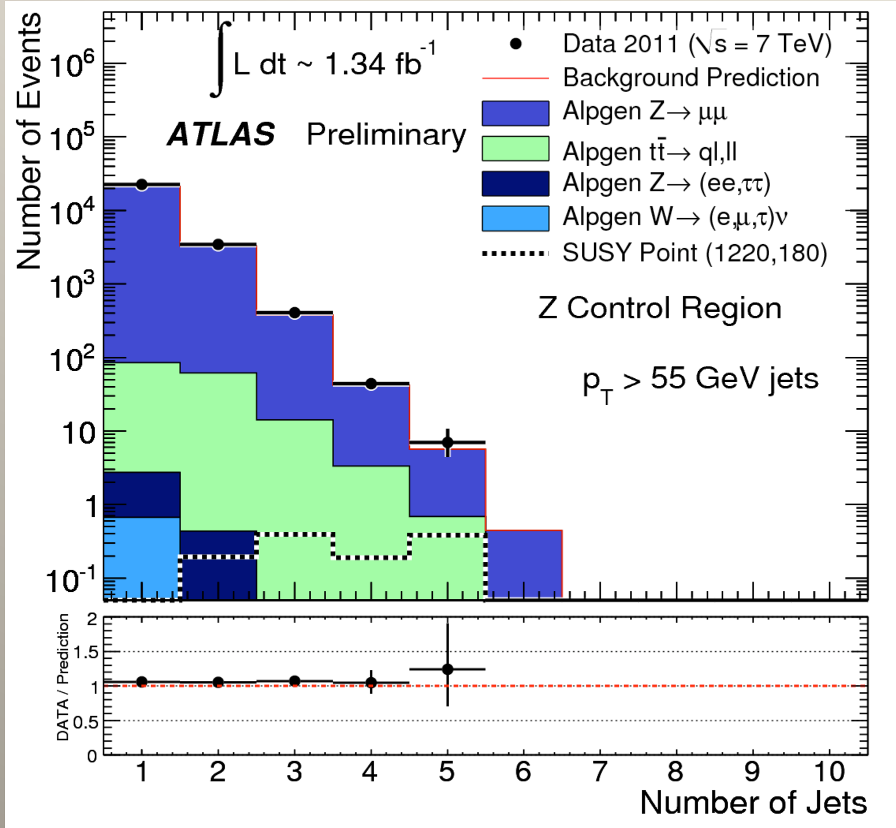


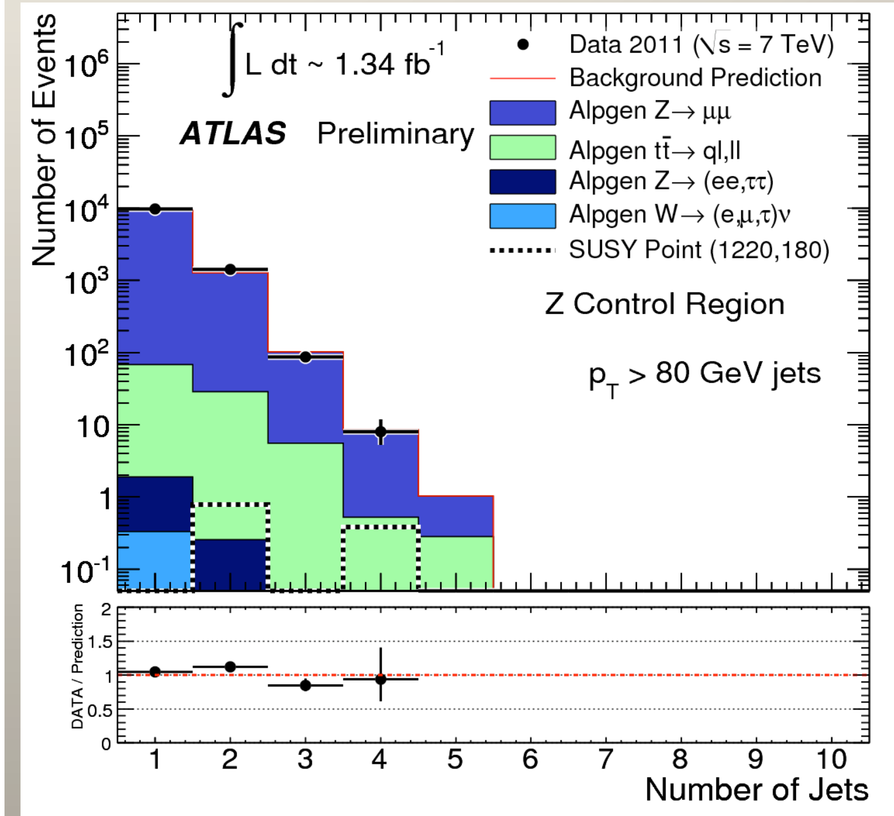
Multijets: W Validation Region



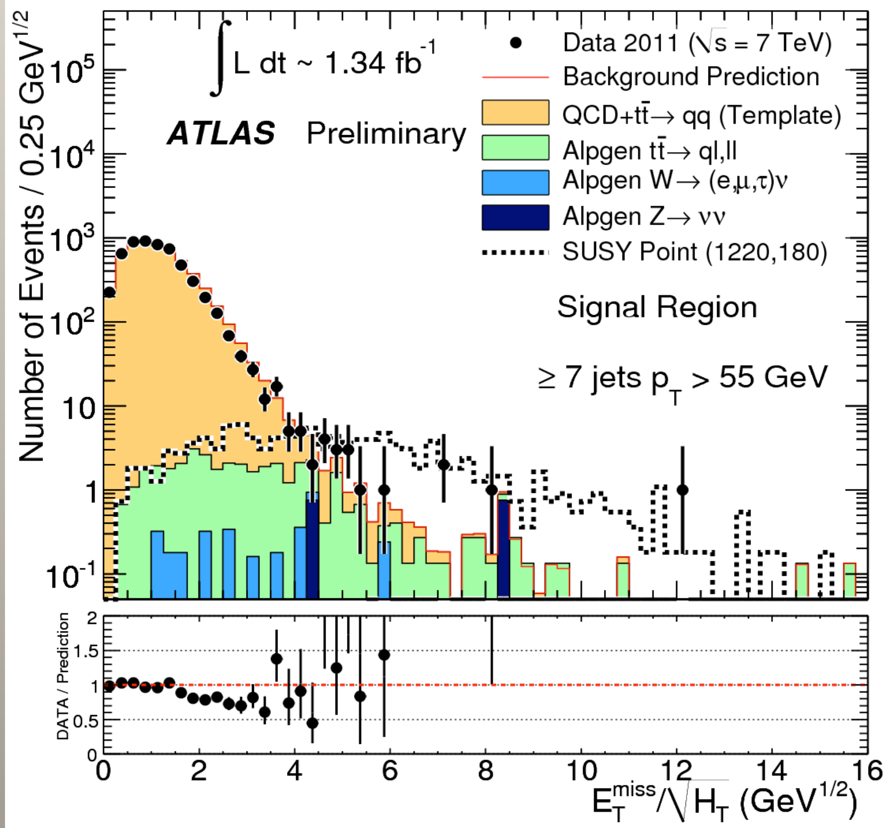


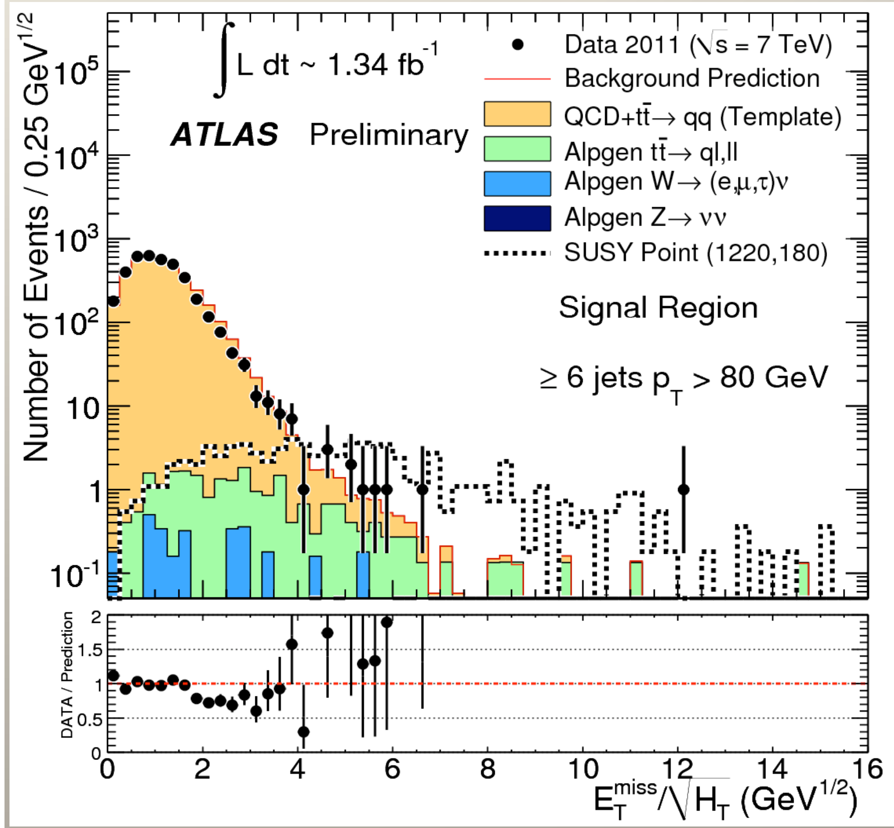
Multijets: Z Validation Region





MET/$\sqrt{H_T}$ in the Signal Regions





6-8 jet study exclusion vs 2010 2-4 jets results